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Rocketry . . . . . Jet Propulsion Sciences . . . . . Astronautics

VOLUME 25 MARCH 1955 NUMBER 3

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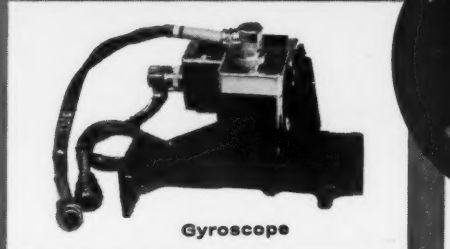

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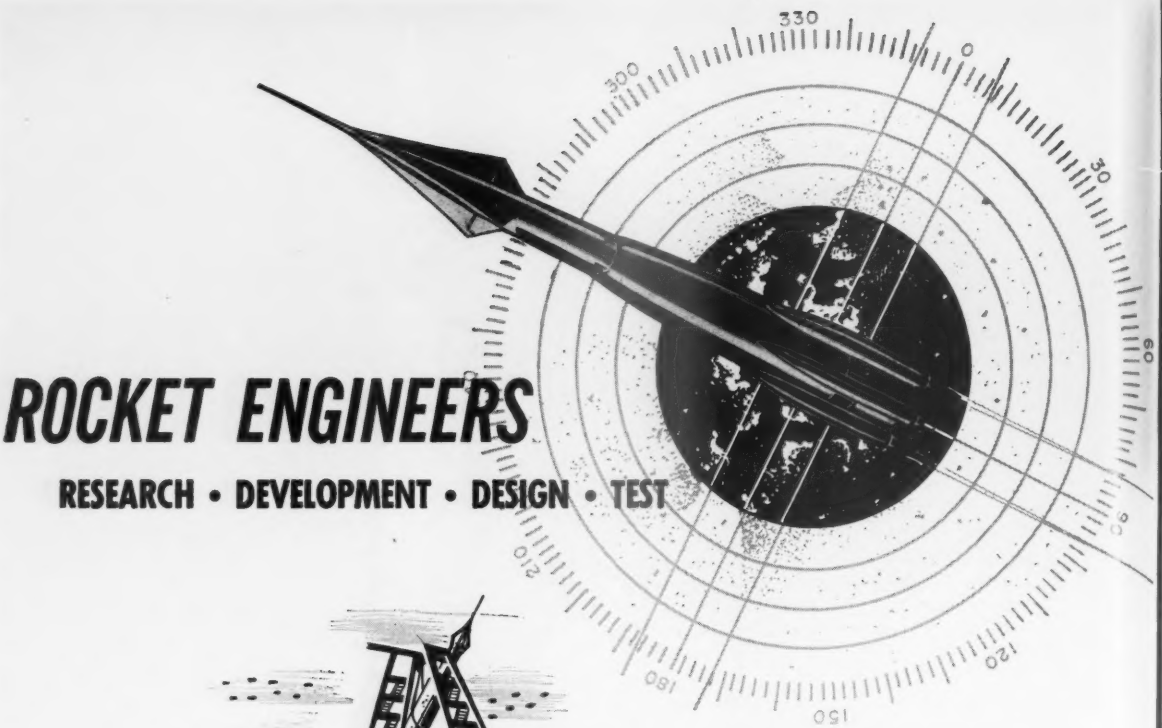

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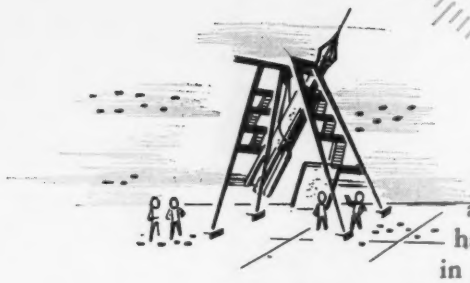

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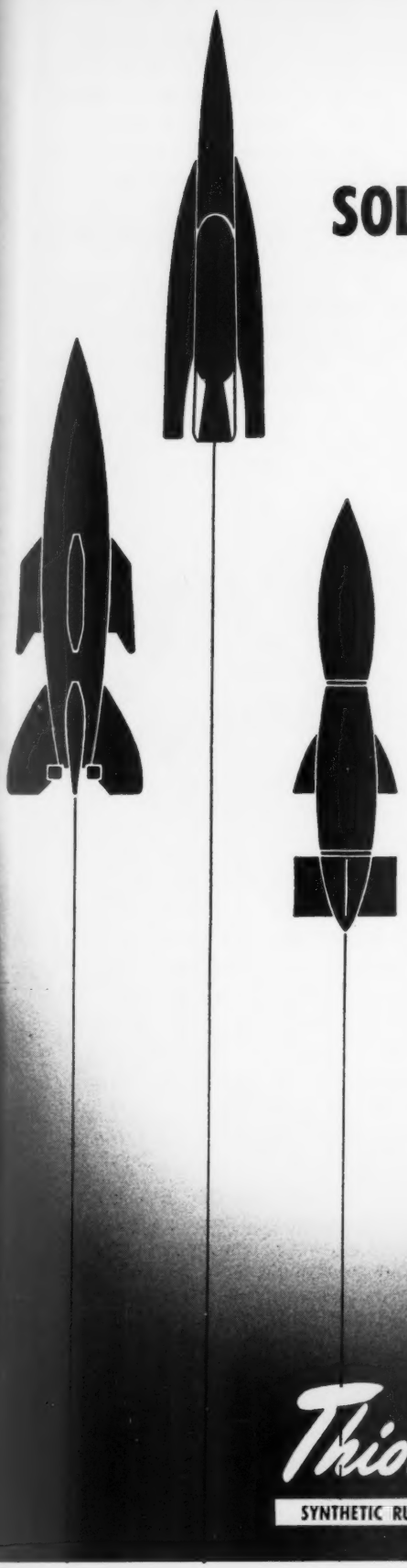

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MARCH 1955

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JET PROPULSION
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Combustion Temperatures and Gas Composition

R. VICHNIEVSKY,[1] B. SALE,[2] and J. MARCADET[2]

Institut Français du Pétrole, Paris, France

The purpose of this paper is to show the possibility of the rapid approximative calculation of the combustion temperatures, taking into account the dissociation phenomena, in a very wide range of thermodynamic conditions. In the second part there is described a simple and accurate method of computation of the gas mixture components at high temperature. This last method can be put in the hands of untrained people. Very good precision is obtained in the results, using only elementary mathematical operations.

Introduction

IN THE PAST twenty years the calculation of the combustion temperature has taken a very important place in the technical and scientific literature (1–5, 7, 14).[3] The first problem was the determination of the different thermodynamic functions, enthalpy, energy, and entropy. The exact evaluation of these functions for the different gaseous mixtures is tedious, for it is necessary to calculate by trial and error method the exact composition of the gas at high temperature, taking into account the six or seven following equilibrium relations:

$2CO_2 \rightleftarrows 2CO + O_2$	(A)	$H_2 \rightleftarrows 2H$	(D)
$2H_2O \rightleftarrows 2OH + H_2$	(B)	$O_2 \rightleftarrows 2O$	(E)
$2H_2O \rightleftarrows 2H_2 + O_2$	(C)	$N_2 + O_2 \rightleftarrows 2NO$	(F)
		$N_2 \rightleftarrows 2N$	(G)

and the four mass balance equations for oxygen, hydrogen, carbon, and nitrogen:[4]

$$2(CO_2) + (CO) + 2(O_2) + (O) + (H_2O) + (OH) + (NO) = l$$
$$2(H_2O) + (OH) + 2(H_2) + (H) = m$$
$$(CO_2) + (CO) = n$$
$$2(N_2) + (NO) + (N) = k$$

where

k = number of gram atomic weights of carbon in the mixture
l = number of gram atomic weights of oxygen in the mixture
m = number of gram atomic weights of hydrogen in the mixture
n = number of gram atomic weights of nitrogen in the mixture

EDITORS' NOTE: The editors solicited this manuscript in order to bring to the attention of American readers a method of combustion analysis that is extremely rapid and accurate as well. A supplementary publication in the near future will give the complete set of working charts for temperatures from 2000 K to 3200 K.

Received September 7, 1953.

[1] Chief, Department of Fuels and Combustibles.

[2] Research Engineer, Department of Fuels and Combustibles.

[3] Numbers in parentheses indicate References at end of paper.

[4] In this manuscript the chemical symbol in parentheses refers to the concentration in moles of the indicated species.

A Approximate Temperature Determinations

Since 1933, a method developed by Prof. G. Ribaud has been used in France for the combustion temperature determination (8, 12, 13). This method is based on the assumption of nonreaction between two series of equilibria, one related to the dissociation of CO_2 and the other to the dissociation of H_2O.

For instance, the combustion of a stoichiometric mixture of heptane-air will give: $7CO_2 + 8H_2O + 41.5N_2$. At high temperatures, $7CO_2$ and $8H_2O$ will undergo dissociation, and the importance of the dissociation energy for each compound such as CO_2 and H_2O will be nearly the same as in the mixture of $7CO_2 + 49.5I_2$ and $8H_2O + 48.5I_2$, respectively, where I_2 is an inert gas. $8H_2O$ is considered as an inert gas in the first case, in the same manner as $41.5N_2$, and in the second case $7CO_2$ is similarly considered inert. This assumption is valuable for the energy problem only, since the composition of the dissociated products will be somewhat different. The effective enthalpy will be formed by two terms, one related to the heating of the final products from the reference temperature up to the combustion temperature, and another related to the dissociation energy at the combustion temperature. The last quantity will depend upon the temperature, the pressure, and the total number of molecules present in the mixture. The tables of effective enthalpies have been given by Ribaud (9, 10, 11). Such tables can be used for the calculation of the effective enthalpy of the mixture $7[CO_2 + 7.07I_2]$ by interpolation between the values corresponding to the mixtures $CO_2 + 4I_2$ and $CO_2 + 8I_2$.

The following results are obtained by this method from Table 1:

Effective Enthalpies (Kcal)

$t°$	$CO_2 + 4I_2$	$CO_2 + 8I_2$	$CO_2 + 7.07I_2$
1900 C (2173 K)	28.60	29.35	29.14
2000 C (2273 K)	32.20	33.40	33.12

Calculated in the exact manner are the effective enthalpies of the mixture $H_2O + 6.06I_2$ corresponding to temperatures 1900 and 2000 C. The necessary data are given in Table 2.

Effective Enthalpies (Kcal)

$t°$	$H_2O + 4I_2$	$H_2O + 8I_2$	$H_2O + 6.06I_2$
1900 C (2173 K)	22.45	23.25	22.86
2000 C (2273 K)	25.30	26.50	25.92

The preceding numbers must be multiplied by the corresponding factors of the combustion equation and added to the enthalpy of the 41.5 moles of nitrogen.

The molar heat of combustion of heptane, 1068 Kcal, indicates immediately the combustion temperature by interpolation between the numbers given in Table 3.

Table 1 Effective Enthalpies (Kcal/Mol) for the Molecule CO_2 between 0 and t C in the Mixtures $CO_2 + pI_2$ at Atmospheric Pressure

t C	CO_2	$CO_2 + 2I_2$	$CO_2 + 4I_2$	$CO_2 + 8I_2$	$CO_2 + 12I_2$	$CO_2 + 16I_2$
1300	16.00	16.04	16.07	16.10	16.15	16.25
1400	17.50	17.57	17.65	17.70	17.80	17.90
1500	19.15	19.30	19.45	19.50	19.75	19.90
1600	20.75	20.95	21.20	21.30	21.45	21.65
1700	22.70	23.05	23.30	23.55	23.90	24.20
1800	24.70	25.35	25.80	26.15	26.55	27.00
1900	27.10	27.90	28.60	29.35	29.90	30.40
2000	29.60	31.00	32.20	33.40	34.40	35.00
2100	32.80	34.70	36.35	38.30	39.50	40.60
2200	36.30	39.00	41.80	44.50	46.20	47.30
2300	40.80	44.70	48.30	51.50	53.60	55.40
2400	46.80	51.80	55.90	60.00	62.50	65.00
2500	53.00	59.40	63.70	68.50	71.30	74.70
2600	60.40	68.30	72.80	78.40	81.80	85.80
2700	68.30	77.50	82.60	89.10	93.10	97.80

Table 2 Effective Enthalpies (Kcal/Mol) for the Molecule H_2O between 0 and t° C in the Mixtures $H_2O + pI_2$ at Atmospheric Pressure

t C	H_2O	$H_2O + 2I_2$	$H_2O + 4I_2$	$H_2O + 8I_2$	$H_2O + 16I_2$
1300	12.50	12.50	12.50	12.50	12.50
1400	13.65	13.65	13.65	13.65	13.65
1500	14.80	14.88	14.95	15.05	15.25
1600	16.00	16.15	16.40	16.65	16.95
1700	17.45	17.60	18.20	18.55	19.05
1800	19.00	19.35	20.15	20.70	21.25
1900	20.80	21.50	22.45	23.25	24.15
2000	23.00	24.00	25.30	26.40	27.50
2100	25.60	26.75	28.25	29.90	31.50
2200	28.70	30.25	32.45	34.50	36.30
2300	32.15	34.60	37.40	40.00	42.40
2400	36.70	40.05	43.75	47.40	51.00
2500	42.20	46.25	51.20	56.25	61.60
2600	48.10	53.80	60.30	66.80	75.40
2700	54.80	60.70	70.80	79.70	91.80

Table 3

Temperature →	1900 C	2000 C
Effective enthalpy of $7CO_2$	204	231
$8H_2O$	181	206
Enthalpy of $41.5N_2$	630	660
	1015 Kcal	1097 Kcal

$$t_c = 1900 + \frac{1068 - 1015}{1097 - 1015} \times 100 = 1900 \text{ C} + \frac{53}{82} \times 100 = 1965 \text{ C or } 2238 \text{ K}$$

This temperature is 17 degrees lower than that calculated by the rigorous method.

The following approximate determination of the composition and the enthalpies of the combustion products at high temperatures under different pressures was conceived by one of the authors (15, 16, 17). This method is based upon a double assumption; first, on the nonreaction between the two series of equilibria as previously indicated; second, on a particular representation of amounts of different gases. In this representation (Fig. 1) every kind of gas is given as a function of the generalized equilibrium constant $(\Sigma/P)K_{O_2}$ where Σ is the total number of moles in the mixture, P the total pressure, and K_{O_2} the equilibrium constant of reaction (E) given by the tables. The logarithmic scale is particularly useful; such a chart only has a meaning when there is a linear relationship between the different equilibrium constants and that of oxygen dissociation. For the first reaction group, A and E, the ratio $(K_{CO_2}/K_{O_2})^{1/2}$ increases from 2.38 to 2.65 when the temperature rises from 2500 to 3000 K. The determination of the components resulting from the dissociation of the CO_2 molecule by this method is satisfactory to within 2 or 3 per cent.

When this method is applied to the second group of reactions, B, C, D, and E, the difference between the values read from the chart and actual ones is more noticeable and the gas composition is only correct to within 10 per cent.

The same representation can be used for the enthalpy of dissociation which is proportional to the amount of the dissociated components. As the dissociation energy is a function

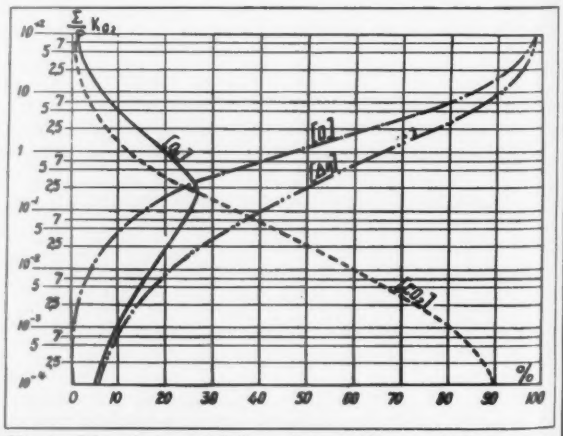

Fig. 1 Dissociation of fictive mixtures $CO_2 + nI_2$ (n is number of inert molecules)

of the temperature, its mean value can be chosen for the range of temperatures between 1750 and 3000 K for each of the components CO_2 and H_2O.

When both molecules CO_2 and H_2O are present in the mixture, the composition of the dissociated products is somewhat modified as well as corresponding enthalpies of dissociation. But for the latter this modification is relatively small, since there is some compensation between the enthalpies of dissociation related to the different equilibria. Furthermore, the energy of dissociation in most technical applications is only a

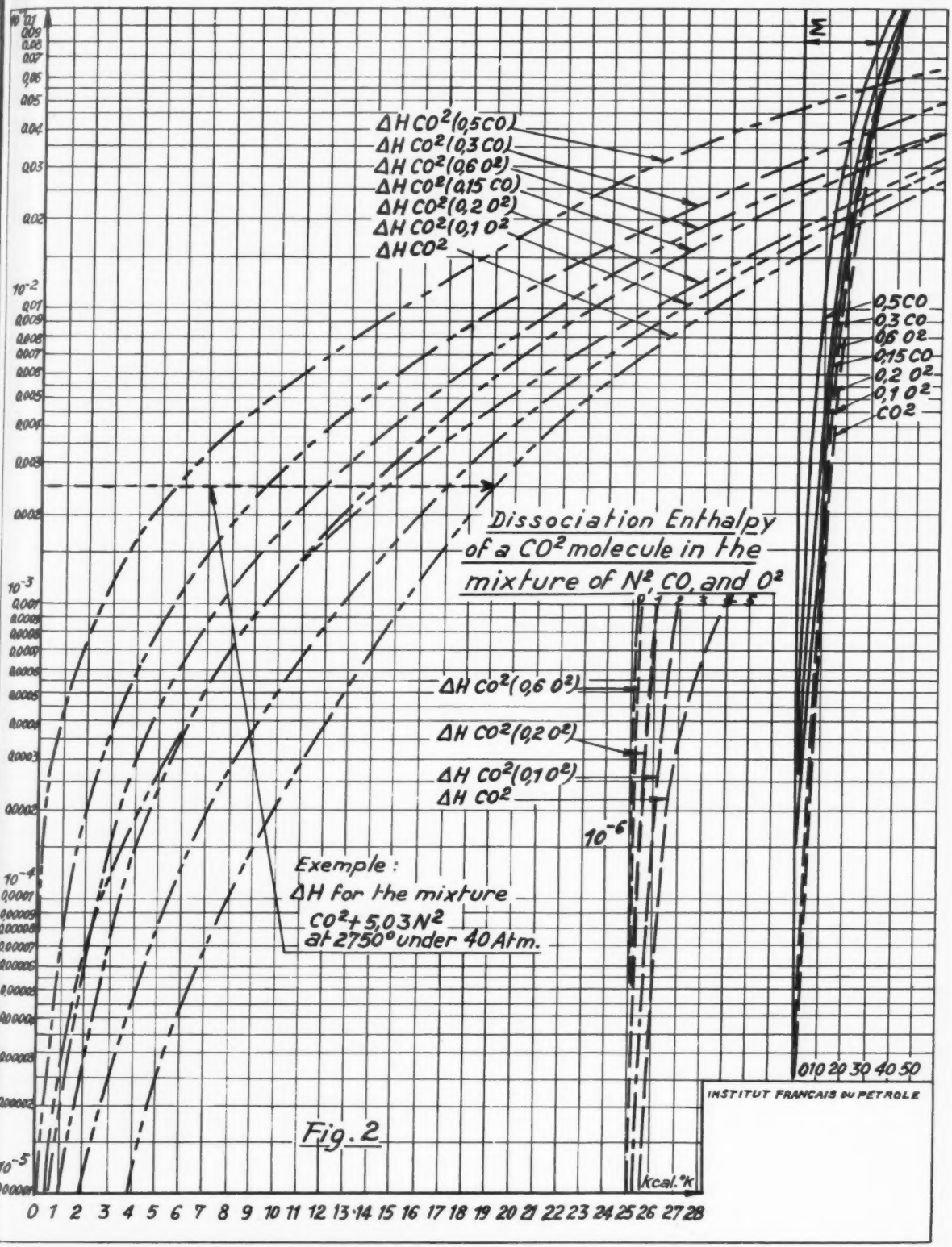
ΔH CO²(0,5 CO)
ΔH CO²(0,3 CO)
ΔH CO²(0,6 O²)
ΔH CO²(0,15 CO)
ΔH CO²(0,2 O²)
ΔH CO²(0,1 O²)
ΔH CO²
0,5 CO
0,3 CO
0,6 O2
0,15 CO
0,2 O2
0,1 O2
CO2
Dissociation Enthalpy of a CO² molecule in the mixture of N², CO, and O²
ΔH CO²(0,6 O²)
ΔH CO²(0,2 O²)
ΔH CO²(0,1 O²)
ΔH CO²
10⁻⁶
Exemple :
ΔH for the mixture
CO² + 5,03 N²
at 2750° under 40 Atm.
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Fig. 2
kcal./°K
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
0 10 20 30 40 50

Fig. 2 Dissociation enthalpies for fictive mixtures $CO_2 + nI_2$ (n is number of inert molecules)

fraction of the total enthalpy, so even when its value is known approximately, the final results are little affected by this approximation. The use of such charts can be illustrated by the following example of combustion of a diesel oil in nitric acid under 30 atmospheres. The first step is the evaluation of the energy involved in this reaction. The formation of a mole of nitric acid from its components H_2, O_2, and N_2 liberates 35.2 Kcal. As the theoretical combustion of a diesel oil ($C_{7.25}H_{13}$) requires 8.4 moles of nitric acid, so 296.5 Kcal will be necessary to transform 8.4 moles to its components. This energy has to be taken from the heat of combustion of the diesel oil (1100 Kcal/mole). A fraction of this energy of de-

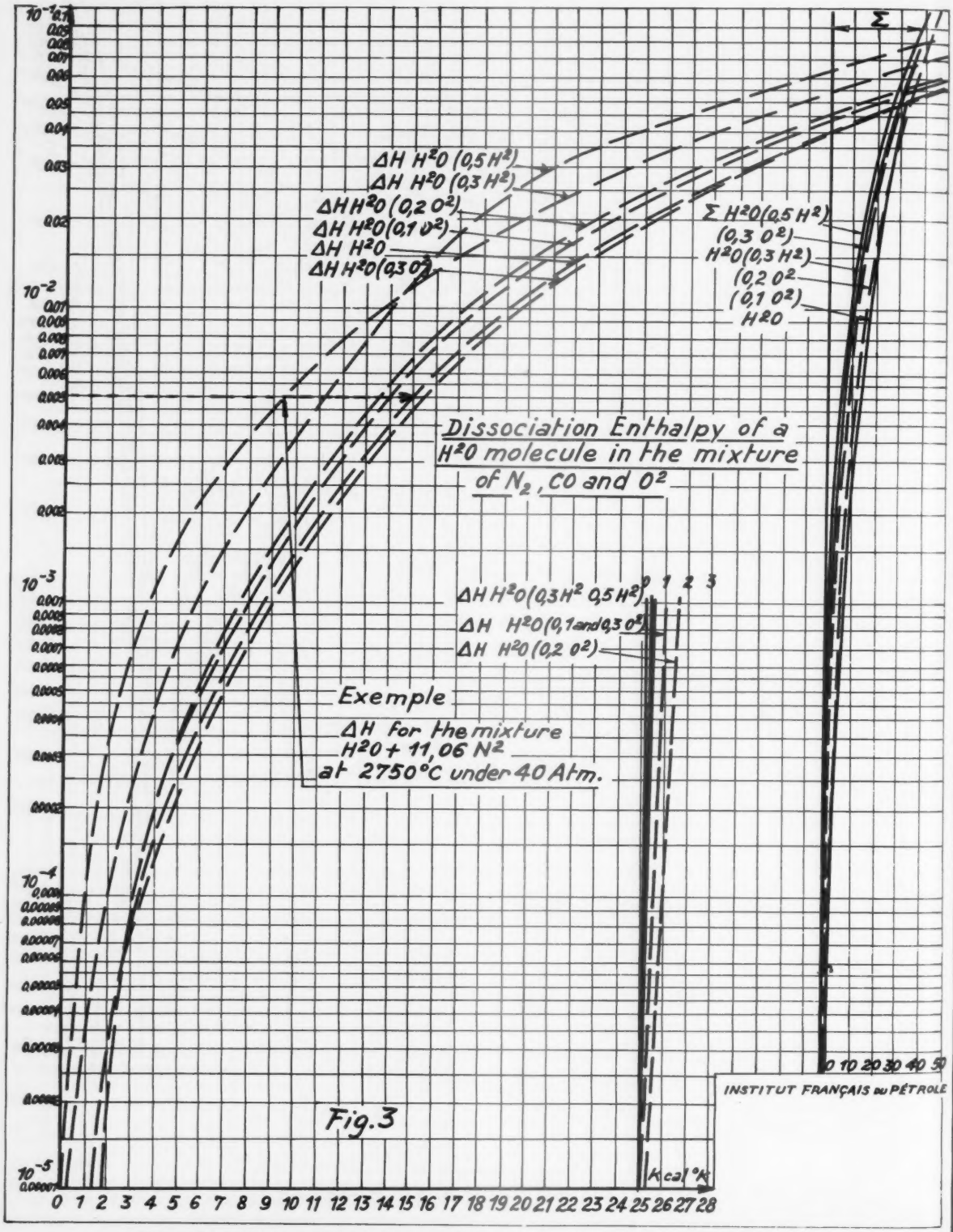
ΔH H²O (0,5 H²)
ΔH H²O (0,3 H²)
ΔH H²O (0,2 O²)
ΔH H²O (0,1 O²)
ΔH H²O
ΔH H²O (0,3 O²)
Σ H²O (0,5 H²)
(0,3 O²)
H²O (0,3 H²)
(0,2 O²)
(0,1 O²)
H²O
Dissociation Enthalpy of a H²O molecule in the mixture of N₂, CO and O²
ΔH H²O (0,3 H² 0,5 H²)
ΔH H²O (0,1 and 0,3 O²)
ΔH H²O (0,2 O²)
Exemple
ΔH for the mixture H²O + 11,06 N² at 2750°C under 40 Atm.
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Fig. 3
Kcal °K

Fig. 3 Dissociation enthalpies for fictive mixtures $H_2O + nI_2$ (n is number of inert molecules)

composition is recovered by the combustion of 8.4 gram atomic weights of hydrogen giving finally 4.2 moles of H_2O and liberating 243.6 Kcal. Assuming a two-step reaction, the combustion equation can be written in the following manner:

$$C_{7.25}H_{13} + 8.4HNO_3 \rightarrow 7.25CO_2 + 10.7H_2O + 4.2N_2 + 1100 - (296.5 - 243.6) = 1047 \text{ Kcal}$$

The next step is the evaluation of the enthalpy of dissociation of CO_2 and H_2O in two fictitious mixtures: $CO_2 + [(10.7H_2O + 4.2N_2)/7.25]$ or $CO_2 + 2.05I_2$, and $H_2O + [(7.25CO_2 + 4.2N_2)/10.7]$, or $H_2O + 1.07I_2$ (molecules between the brackets are considered as an inert gas). The data on the equilibrium constants give for $K_{O_2} = (O)^2/(O_2)$ the values 4.20×10^{-2} and 7.9×10^{-2} corresponding respectively to the temperatures of 2900 and 3000 C, which will be assumed to represent the lower and higher limits of the possible combustion temperature. In order to use the generalized constant charts, the preceding values must be multiplied by the quotient of the number of moles by the pressure (the real number of moles taking into account the dissociation can be read from the right-hand side of Figs. 2 and 3).

On first approximation the generalized constants at 2900 and 3000 C are as follows:

$$\frac{3.05 \times 4.2 \times 10^{-2}}{30} = 4.25 \times 10^{-3} \quad \text{and}$$

$$\frac{3.05 \times 7.9 \times 10^{-2}}{30} = 8 \times 10^{-3} \text{ for } CO_2 \text{ equilibrium}$$

$$\frac{2.07 \times 4.2 \times 10^{-2}}{30} = 2.9 \times 10^{-3} \quad \text{and}$$

$$\frac{2.07 \times 7.9 \times 10^{-2}}{30} = 5.5 \times 10^{-3} \text{ for } H_2O \text{ equilibrium}$$

They allow the determination of the total number of molecules, and their new values are:

$$\frac{3.22 \times 4.2 \times 10^{-2}}{30} = 4.5 \times 10^{-3} \quad \text{and}$$

$$\frac{3.25 \times 7.9 \times 10^{-2}}{30} = 8.5 \times 10^{-3} \text{ for } CO_2 \text{ equilibrium}$$

$$\frac{2.18 \times 4.2 \times 10^{-2}}{30} = 3.05 \times 10^{-3} \quad \text{and}$$

$$\frac{2.22 \times 7.9 \times 10^{-2}}{30} = 5.9 \times 10^{-3} \text{ for } H_2O \text{ equilibrium}$$

For instance, the dissociation enthalpy of CO_2 in the mixture $CO_2 + 2.05I_2$ at 2900 C read from Fig. 2 is 22.5 Kcal. All calculations related to the combustion of diesel oil in nitric acid are summarized in Table 4.

Simple interpolation between these two values of enthalpy gives the combustion temperature

$$2900 + \frac{1047 - 1031}{1115 - 1031} \times 100 = 2900 + 19 = 2919 \text{ C}$$

The comparison of this temperature with the result when the dissociation phenomenon is neglected shows a difference of 3970 − 2919 = 1051 C. The relative error is about 35 per cent. The same temperature compared with that one calculated by the rigorous method points out a difference of only 40 C, or 1.5 per cent, which is quite reasonable for technical needs.

The use of such a method for the determination of the flame speed based upon the concentration of several compounds is less favorable, as shown in Table 5.

The difference between the dissociation enthalpies calculated with two different methods represents only an error of 8 per cent, which is less than 2.6 per cent in the total enthalpy of the combustion products. This points out that the method of generalized dissociation constants can be used acceptably for the rapid determination of the combustion temperatures,

Table 4

Fictitious equilibrium	Generalized const.	Enthalpy of dissociation per mole, Kcal/mole	Enthalpy of dissociation for total moles, Kcal	Enthalpy of heating per mole, Kcal/mole	Enthalpy of heating for total mole, Kcal	Total effective enthalpy for total moles, Kcal
Temperature 2900 C						
$CO_2 + 2.05I_2$	4.5×10^{-3}	22.5	7.85 × 22.5 = 162	39.35	285	447
$H_2O + 1.07I_2$	3.05×10^{-3}	12.8	10.7 × 12.8 = 138	32.35	346	484
N_2				23.89	4.2 × 23.89	100
						1031
Temperature 3000 C						
$CO_2 + 2.05I_2$	8.5×10^{-3}	26.5	7.25 × 26.5 = 192	40.5	7.25 × 40.8 = 293	485
$H_2O + 1.07I_2$	5.9×10^{-3}	15.6	10.7 × 15.6 = 166	33.8	10.7 × 33.8 = 360	526
N_2				24.78	4.2 × 24.78 = 104	104
						1115

Table 5 Combustion Products of a Diesel Oil in Nitric Acid at t = 2973 C (3246 K) and P = 30 atm

	Trial and error method: number of moles	Generalized constant method: number of moles	Difference	Relative difference, %	Dissociation energy difference, Kcal
CO_2	4.672	4.63	−0.042	− 0.9	
CO	2.578	2.618	+0.04	+1.5	+2.6
O_2	1.297	1.571	+0.274	+21	
H_2O	9.340	8.94	−0.4	−4.3	
H_2	0.700	1.18	+0.48	+69	+36
OH	1.130	0.813	−0.317	−40	−22
O	0.266	0.395	+0.129	+50	+7.2
H	0.240	0.304	+0.064	+25	+3.5
					27.3 Kcal

but is not suitable and even dangerous for calculations which require the exact composition of gases at high temperatures. This is the reason for which the development of a new method, as described in the following section, was undertaken.

B Exact Calculation of the Composition of Combustion Products at High Temperatures

The method (18) presented here permits rapid and rigorous calculation of the gas mixture composition at high temperatures under different pressures ($P > 0.01$ atm) when these mixtures are initially formed exclusively of carbon, hydrogen, oxygen, nitrogen, and inert gases, such as argon, neon, etc.

A series of graphs have been established for the temperature range from 2000 to 3200 K, taking into account the following equilibria:

$$2CO_2 \rightleftarrows 2CO + O_2 \qquad 2H_2O \rightleftarrows 2H_2 + O_2$$
$$O_2 \rightleftarrows 2O \qquad H_2 \rightleftarrows 2H$$
$$2H_2O \rightleftarrows 2OH + H_2 \qquad N_2 + O_2 \rightleftarrows 2NO$$
$$N_2 \rightleftarrows 2N$$

The equilibrium constants published by the National Bureau of Standards (19) and that of French Petroleum Institute (6) were used for these calculations. The last reaction was considered only for the determination of gas mixture composition at 3200 K. At lower temperatures the value of the corresponding equilibrium constant is so small that nitrogen dissociation can be practically neglected.

Theory of the method

The relations giving the mixture composition can be written in the following form.

$$\frac{(CO)^2\,(O_2)}{(CO_2)^2} = K_1 V \qquad [1]$$

$$\frac{(O)^2}{(O_2)} = K_2 V \qquad [2]$$

$$\frac{(OH)^2(H_2)}{(H_2O)^2} = K_3 V \qquad [3]$$

$$\frac{(H_2)^2(O_2)}{(H_2O)^2} = K_4 V \qquad [4]$$

$$\frac{(H)^2}{(H_2)} = K_5 V \qquad [5]$$

$$\frac{(NO)^2}{(N_2)(O_2)} = K_6 \qquad [6]$$

$$\frac{(N)^2}{(N_2)} = K_7 V \qquad [7]$$

$$(CO_2) + (CO) = n \qquad [8]$$

$$2(H_2) + 2(H_2O) + (OH) + (H) = m \qquad [9]$$

$$2(N_2) + (NO) + (N) = k \qquad [10]$$

$$2(CO_2) + (CO) + 2(O_2) + (O) + (H_2O) + (OH) + (NO) = l \qquad [11]$$

V is the volume occupied by the mixture, K equilibrium constants at the constant volume. These constants can be deduced from the relation $K = K'(1/RT)^{\delta}$ where K' is the equilibrium constant at a constant pressure, and δ is the algebraic sum of the exponents in these preceding relations: i.e.,

n = total gram atomic weights of carbon
m = total gram atomic weights of hydrogen
l = total gram atomic weights of oxygen
k = total gram atomic weights of nitrogen

Equations [1], [2], [3], [4], [5], and [9] determine the values of O_2/m, O/m, H_2O/m, OH/m, H/m, H_2/m as functions of two variables: the ratio CO/CO_2 (or CO/n) and V/m independently of the different values of n, l, m, and k.

Similarly, Equations [6], [7], and [10] define N_2/k, NO/k and N/k as functions of two variables O_2/k and V/k independently of the mixture characteristics.

The Graphs B, C, D (Figs. 5, 6, and 7), and E[5] give reduced composition versus two parameters: the ratio CO/n (or appropriate function of this ratio) and the reduced volume V/m.

Graph A (Fig. 4) is used for the calculation of the ratio CO/n necessary for the computation on preceding charts. This representation (Graph A) is based on the relation [11] (oxygen balance) which was not introduced until now and which can be written in the following form:

$$\frac{2O_2}{m} + \frac{O}{m} + \frac{H_2O}{m} + \frac{OH}{m} = \frac{l - 2n}{m} + \frac{n}{m}\left(\frac{CO}{n}\right) - \frac{k}{m}\frac{NO}{k}$$

On Graph A are represented the value $a(V/m, CO/n) = (2O_2/m) + (O/m) + (H_2O/m) + (OH/m)$ versus two variables CO/n and V/m.

If the term NO is neglected, the required value CO/n is the abscissa of the intersection point of the curve $a(CO/n, V/m)$ with the straight line, $a = [(l - 2n)/m] + (n/m)\,(CO/n)$.

It is possible to take into account the term NO by the trial-and-error method. When NO is neglected, the value CO/n given by the chart permits the calculation of the term NO. A further approximation consists of drawing a new line

$$a = \frac{l - 2n - k\,(NO/k)}{m} + \frac{n}{m}\left(\frac{CO}{n}\right)$$

parallel to the first one which gives a new intersection point with the curve $a(V/m, CO/n)$. This point gives new values of CO/n and NO. The last operation can be done as long as different values NO are found. Practically only one approximation is necessary, for the convergence of the calculations is very rapid.

This application of these charts is easily extended to the case where the imposed parameter is the pressure of the mixture and not its volume. For this reason there were drawn curves on Graph C:

$$\frac{\sigma H}{m} = \frac{H_2O + OH + H + H_2 + O_2 + O}{m} =$$

function of two variables V/m and a

Description of the charts

The theoretical principle of the described method is rigorous and errors of results depend only upon the accuracy of the execution of the graphs. This is the reason for the limitation to key variables which are used in elementary calculations of the mixture composition; with the scales employed for such representation, errors are about 1 or 2%, so are less than these introduced by our knowledge of the thermodynamic data.

The key variables were chosen according to their nature either as functions of CO/n and V/n, or as a function of a and V/m, or at least as function of O_2/k and V/k. On the other hand, a change of variable was made so as to obtain values independent of the reduced volume.

For each temperature there were established:

1 A Graph A giving curves $a = f(CO/n, V/m)$.

2 A Graph B giving, first, the curves $H_2/m = f(CO/n, V/m)$ and, second, the curves

$$\frac{O_2}{V} = f\left(\frac{CO}{n}\right);\ \frac{O}{V} = f\left(\frac{CO}{n}\right);\ \frac{NO}{k}\sqrt{\frac{1}{V/k}} = f\left(\frac{CO}{n}\right)$$

These last relations are independent of the volume. All curves are plotted on a semilogarithmic scale. The first part B_1 is available for $O < (CO/n) < 0.5$ and the second B_2 for $0.5 < (CO/n) < 1$.

3 A Graph C related, first, to the curves $\sigma H/m = f(a, V/m)$ and, second, to the curves $(H_2O/m) = f(a, V/m)$, [with

[5] Graph E refers to dissociation of N_2. It is a part of the 3200 K set of graphs to be published at a later date.

$0.4 < a < 2.4$], which is represented on a linear scale.

4 A Graph D with curves $O_2/m = f(a, V/m)$ on a semilogarithmic scale.

5 A Graph E with two sets of curves: $NO/k = f(O_2/k, V/k)$, and $N_2/k = f(O_2/k, V/k)$ on a semilogarithmic scale.

Graph E was constructed only for temperatures higher than 3000 K when monatomic N appears. At lower temperatures between 2800 and 3000 K, when the dissociation $N_2 \rightleftarrows 2N$ can be neglected, two scales presented on Graph A give NO/k versus O_2/k for $(NO/k) > 0.01$. When the value NO/k is still less, then the curve $(NO/k) \cdot [1/\sqrt{V/k}] = f(CO/n)$ of Graph B will be used.

Utilization of the charts

Following the nature of the problem to be solved (combustion with constant volume or constant pressure) the variable specific volume or pressure will be introduced in the calculations.

a Composition of a Mixture Without Nitrogen in a Given Volume at a Given Temperature

On the Graph A the intersection point of the line $a = [(l - 2n)/m] + (n/m)\,(CO/n)$ and the curve $a(V_0/m, CO/n)$ is representative of the mixture composition. V_0 is the given volume.

This point gives, by mere reading of the graph, values of CO/n and $CO_2/n = 1 - (CO/n)$. This value of CO/n permits entry on Graph B for the determination of H_2/m. With the value of H_2/m it is easy to calculate:

$$\frac{H}{m} = \sqrt{K_5 \cdot \frac{H_2}{m} \cdot \frac{V}{m}}; \qquad \frac{OH}{H_2O} = \sqrt{K_3 \cdot \frac{V}{H_2}}$$

$$\frac{H_2O}{m} = \frac{1 - (2H_2/m) - (H/m)}{2 + (OH/H_2O)} \quad \text{and} \quad \frac{OH}{m} = \left(\frac{H_2O}{m}\right)\left(\frac{OH}{H_2O}\right)$$

In the same way one calculates from this graph O_2/V and O/V. All necessary relations and numerical values of the equilibrium constants are given on the graphs.

b Composition of a Mixture with Nitrogen in a Given Volume and at a Given Temperature

At first approximation the determination of the representative point is exactly the same as before. The CO/n value read on Graph A is used with Graph B in order to find NO/k

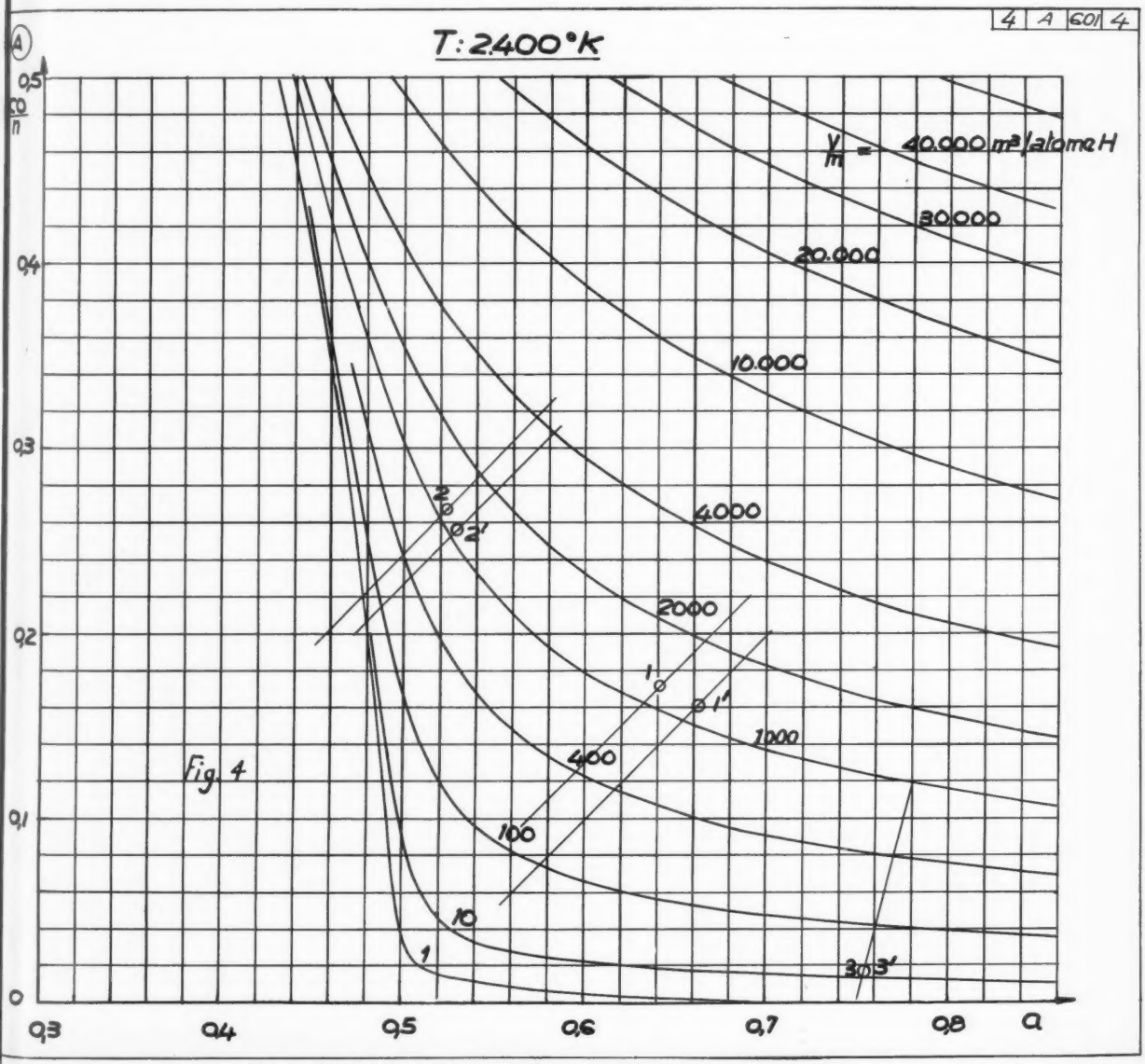

Fig. 4 Graph A for the determination of the CO component in the mixture

$\sqrt{1/(V/k)}$. In the case where the value NO/k calculated from the last relation is larger than 0.04, better precision (error less than 2 per cent) for the temperatures 2800 and 3000 K is given by two scales represented on Graph A, corresponding respectively to these temperatures. For the temperature of 3200 K the value of O_2 read on Graph B will be employed for this purpose. The value obtained by either method allows a new straight line, $a = [(l - 2n - NO)/m] + (n/m)\ (CO/n)$, to be drawn on Graph A. The intersection point with the curve V_0/m indicates a new value of the ratio CO/n. It can be easily seen that the required accuracy is practically reached after a single operation. H_2/m, H/m, OH/m, H_2O/m, O_2/m, O/m are calculated, as explained before. At temperatures lower than 3000 K the proportion of the molecular and atomic nitrogen can be determined by the following relations: $N_2 = (k - NO)/2$ and $N/k = \sqrt{K_7(N_2/k)}\ (V/k)$; at higher temperatures the molecular nitrogen is read directly on Graph E and the atomic nitrogen is given by the preceding relation.

c Composition of a Mixture (General Case) at a Given Pressure and Temperature

The intersection of the line $a = (l - 2n)/m + (n/m)\ [(CO)/n]$ with the curve corresponding to the relation $V_0/m = (\Sigma_0/m)\ (RT/P)$ (where Σ_0 is the number of moles when dissociation is neglected) gives the first approximation of a, and on Graph C, the value of $\sigma H/m$. With this latter value the actual number of moles can be easily calculated $\Sigma/m = (\sigma H/m) + (n/m) + \{[(NO) + k]/2m\}$ where (NO) is determined by the previously expressed method. The intersection of a new line, $a = \{[l - 2n - (NO)]/m\} + \{(n/m)\ [(CO)/n]\}$, with the curve of the volume $V/m = (\Sigma/m)\ (RT/P)$ gives a sufficient approximation for further calculation of gas mixture.

d Particular Cases—Composition Point Corresponds to $(CO)/n < 0.05$

The choice of the linear coordinates has the advantage of simplifying the representation of different parameters, but

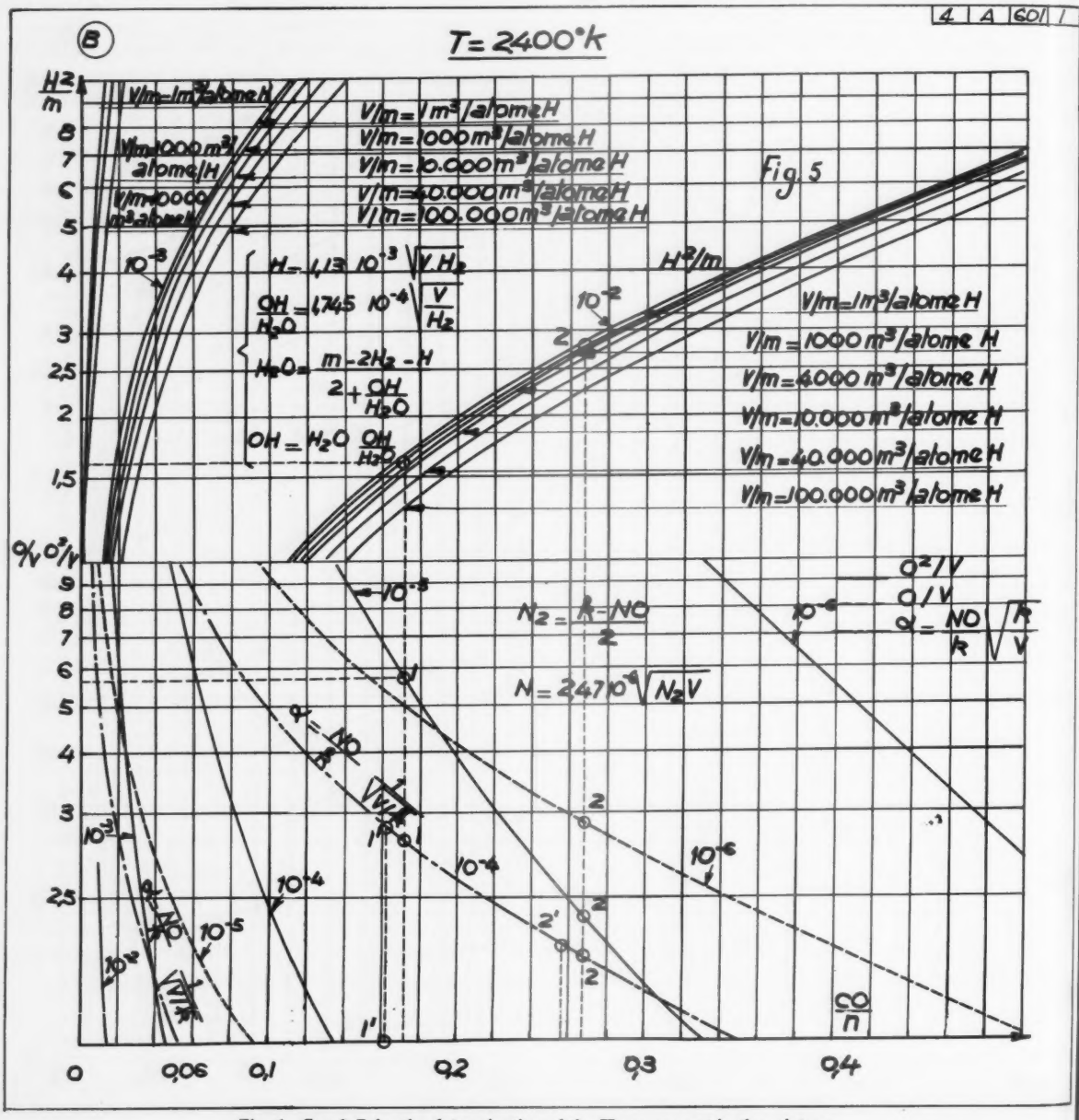

Fig. 5 Graph B for the determination of the H_2 component in the mixture

unfortunately the relative precision of such graphs is bad for low values of the ratio $(CO)/n$ (2% error). This error can be neglected in the evaluation of the thermodynamic functions such as enthalpy, energy, and entropy; but in some cases a better precision may be required.

i *Composition point in the portion of the plane defined by* $(CO)/n < 0.1$ *and* $a > 0.6$.

When the characteristic line of the mixture has been drawn on Graph A, the corresponding value $(O_2)/m = f(a, V/m)$ from Graph D gives $(NO)/k = 0.707\sqrt{K_6[(O_2)/k)]}$ and, as previously, $\sigma H/m$ from the Graph C, and finally the exact composition point on Graph A.

(CO_2) and (CO) are easily calculated by the relation $(CO_2)/(CO) = \sqrt{(O_2)/K_1V}$, taking into account the value O_2/m. On the other side the same chart gives the ratio $(H_2O)/m$ which is necessary for the determination of the different components containing H; for instance, $(H_2)/m = \sqrt{K_4/K_1} \times [(H_2O)/m] \times [(CO)/(CO_2)]$.

The atomic oxygen is calculated directly with the relation: $(O) = \sqrt{K_2V(O_2)}$.

This method is characterized by very high accuracy (the relative error is less than one per cent) even when the dissociation is low. It can be used as well as the general method systematically for all representative points of the plane portion of coordinates $(CO)/n < 0.1$ and $a > 0.6$.

The corresponding curves of $(H_2O)/m$ are represented on Graph C. This particular case is relative to mixtures with excess air or oxygen at low temperatures and high pressures.

ii *The representative point is in the portion of the plane* $(CO)/n < 0.05$ *and* $a < 0.6$.

If a high relative precision is required, the following equation obtained by the combination of Equations [9] and [11] can be resolved graphically for (CO).

$$(H_2O)\sqrt{\frac{K_3}{(m/n)\,\rho}\frac{V}{(CO)}} + 4K_1V\left(\frac{n-(CO)}{(CO)}\right)^2 + 2\left(\frac{n-(CO)}{(CO)}\right)\times$$
$$\sqrt{K_1K_2 + \frac{K_6K_1k}{2}} - \sqrt{K_5V(m/n)\rho(CO)} - 2\left(\frac{m}{n}\rho + 1\right)(CO)$$
$$= 2l = m - 4n \ldots . [12]$$

(H_2O) is read on Graph C; V is calculated taking into account the value $\sigma H/m$ given by Graph C. The values of ρ are reported in Graph I[6] for different temperatures and volumes. In some cases several terms of Equation [12] can be neglected. The value obtained for (CO) immediately gives $(H_2)/m = \rho[(CO)/n]$.

Auxiliary graphs can be constructed for the graphical resolution of Equation [12].

e *Interpolation versus Temperature*

For temperature ranges between those given on the graphs, the gas composition or partial pressure can be plotted on logarithmic scale versus $1/T$. The representative curve in the range of 200 deg can be perfectly assimilated to a straight line with a sufficiently high accuracy.

Illustrative Examples

I *Composition of the combustion products of benzene in air (stoichiometric mixture) at* $T = 2400$ *K and* $P = 1$ *atm:*

The combustion reaction

$$C_6H_6 + 7.5O_2 + 28.2N_2 = 6CO_2 + 3H_2O + 28.2N_2$$

[6] To be published in a supplementary paper.

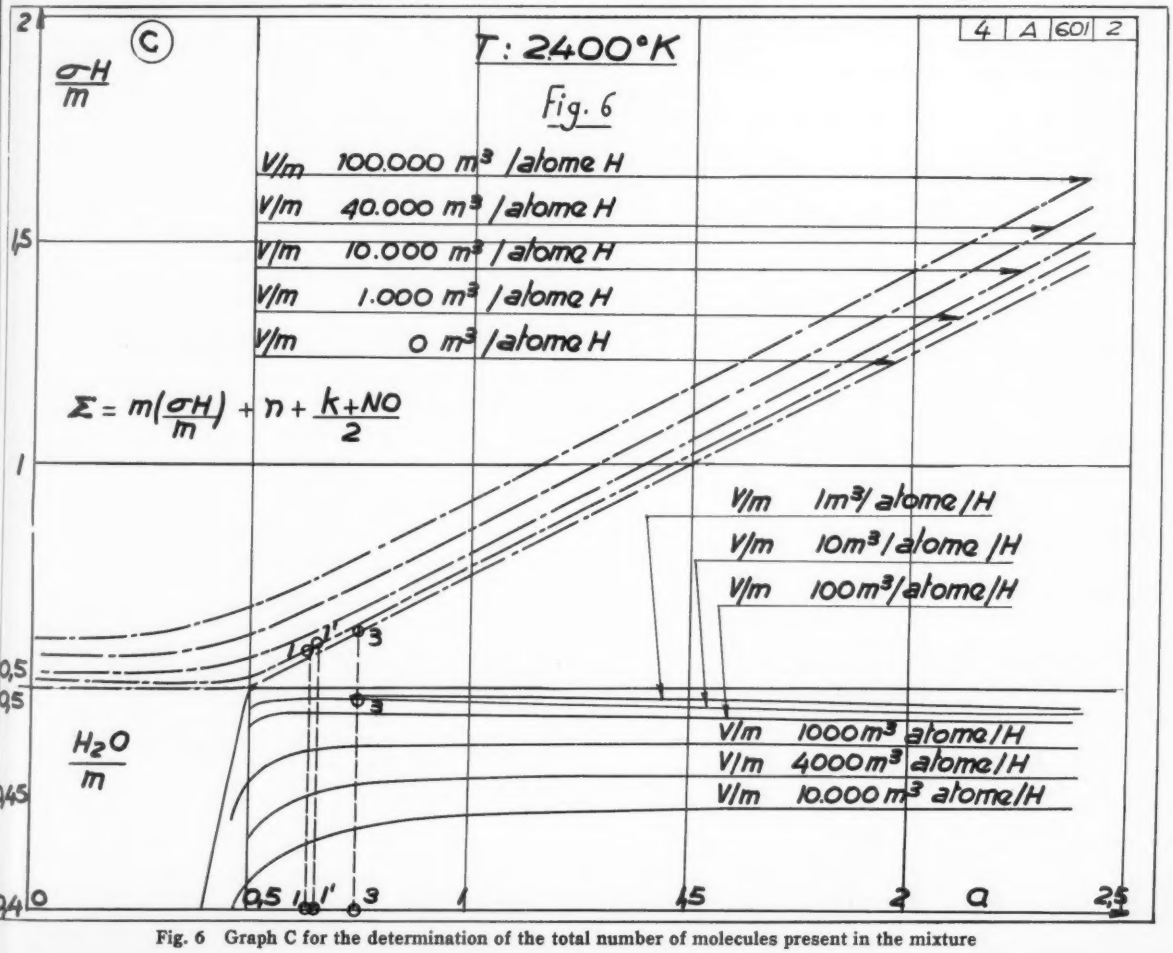

Fig. 6 Graph C for the determination of the total number of molecules present in the mixture

gives the necessary numerical values of the different parameters.

$$n = 6,\ m = 6,\ l = 15,\ k = 56.4,\ \Sigma_0 = 37.2$$

$$V_0 = \frac{\Sigma_0 RT}{P} = \frac{37.2 \times 0.0821 \times 2400}{1} = 7.330\ m^3$$

The line $a = [(l - 2n)/m] + (n/m)\ [(CO)/n]$ has an intersection point with the abscissa at $a = 0.5$; $(CO)/n = 0$. It can be pointed out that for all stoichiometric mixtures when the formation of (NO) is neglected, the characteristic lines cross the abscissa at this point.

Linear interpolation following the abscissa gives immediately the point corresponding to the reduced volume $V_0/m = (7330/6) = 1221\ m^3$.

The coordinates of this point are: $(CO)/n = 0.162$ and $a = 0.662$ (Fig. 4, Graph A). On Fig. 5 (Graph B), for $(CO)/n = 0.162$, the function $(NO)/k\sqrt{k/V}$ has the value 2.82×10^{-4}. $(NO)/m$ is immediately deduced from the following relation

$$\frac{(NO)}{m} = 2.82 \times 10^{-4}\sqrt{\frac{7330}{56.4}} \times \frac{56.4}{6} = 3.03 \times 10^{-3}$$

which is used for the calculation of actual number of moles. Fig. 6 (Graph C) gives for $a = 0.662$ and $V/m = 1221\ m^3$, $\sigma H/m = 0.605$.

The total actual number of moles is:

$$\Sigma = \frac{m\sigma H}{m} + n + \frac{(NO) + k}{2} = 6 \times 0.605 + 6 + \frac{6 \times 3.03 \times 10^{-3} + 56.4}{2} = 37.92$$

and the corresponding volume $V = 7470\ m^3$.

A new representative point on Fig. 4 (Graph A) is given by the intersection point of line $a = [(l - 2n)/m] + [(NO)/m] + (n/m)\ [(CO)/n]$ or $a = 0.4697 + [(CO)/n]$ with the volume curve $V/m = 7470/6 = 1245\ m^3$.

The coordinates of this point are $(CO)/n = 0.172$ and $a = 0.641$. The corresponding numerical values of $(NO)/k\sqrt{k/V}$

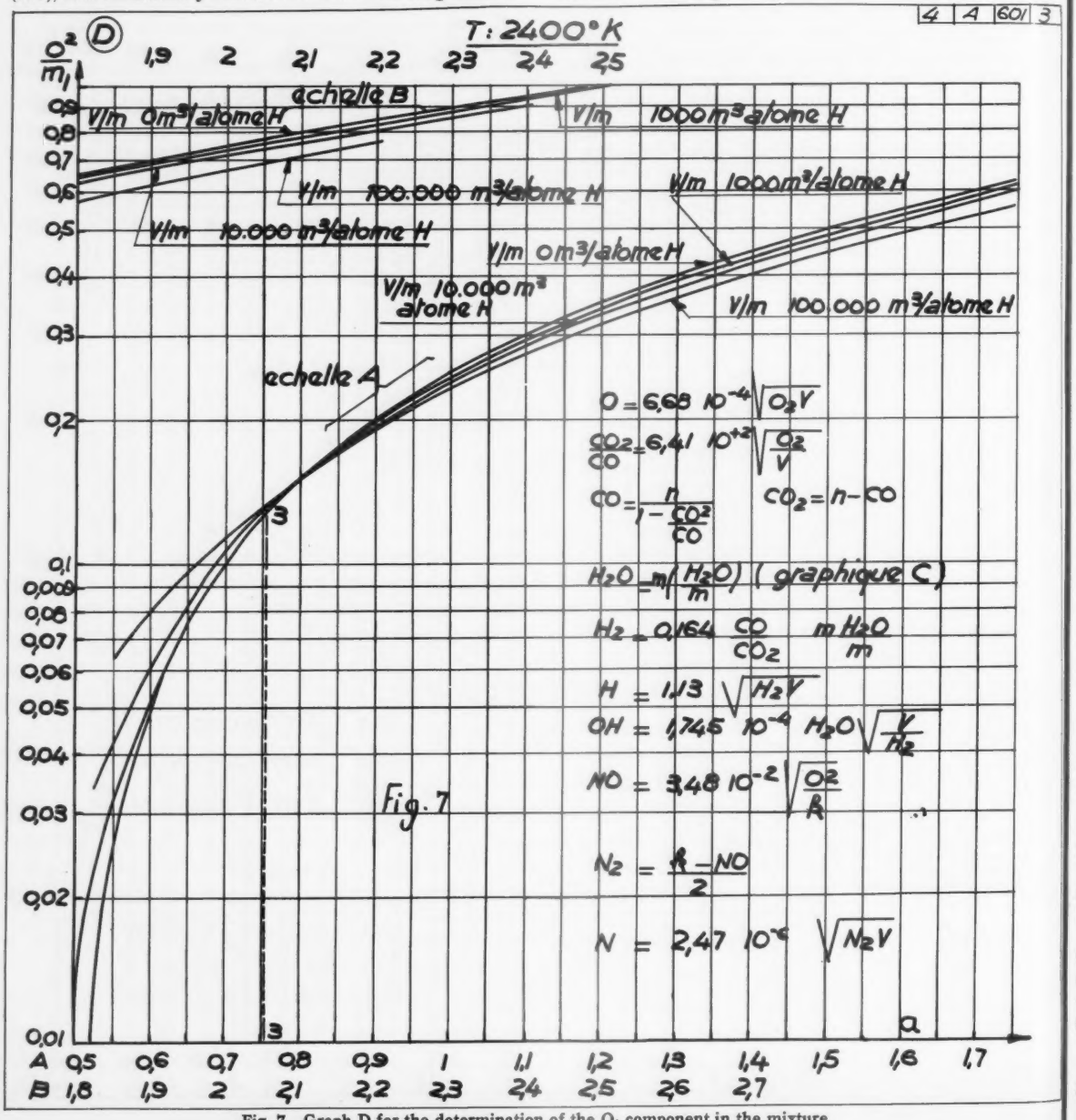
T: 2400°K
4 A 601 3
échelle B
échelle A
V/m 0 m³/atome H
V/m 1000 m³/atome H
V/m 100.000 m³/atome H
V/m 1000 m³/atome H
V/m 10.000 m³/atome H
V/m 0 m³/atome H
V/m 10.000 m³ atome H
V/m 100.000 m³/atome H
O = 6,68 10⁻⁴ √(O₂V)
CO₂/CO = 6,41 10⁺² √(O₂/V)
CO = n / (1 − CO²/CO)
CO₂ = n − CO
H₂O = m(H₂O)/m (graphique C)
H₂ = 0,164 CO/CO₂ m H₂O/m
H = 1,13 √(H₂V)
OH = 1,745 10⁻⁴ H₂O √(V/H₂)
NO = 3,48 10⁻² √(O₂/R)
N₂ = R − NO / 2
N = 2,47 10⁻⁶ √(N₂V)
Fig. 7
A 0,5 0,6 0,7 0,8 0,9 1 1,1 1,2 1,3 1,4 1,5 1,6 1,7
B 1,8 1,9 2 2,1 2,2 2,3 2,4 2,5 2,6 2,7

Fig. 7 Graph D for the determination of the O_2 component in the mixture

$= 2.63 \times 10^{-4}$ and $\sigma H/m = 0.595$, furnish $(NO)/m = 2.63 \times 10^{-4}\sqrt{7470/56.4} \times 56.4/6 = 2.84 \times 10^{-2}$, the new true number of moles $\Sigma = 6 \times 0.595 + 6 + [(6 \times 2.84 \times 10^{-2} + 56.4)/2] = 37.85$ and the new volume $V = 7.450\ m^3$. The corresponding representative point on Fig. 4 has for ordinate value $(CO)/n = 0.171$; the difference with the previous value is less than 0.6%. This value can be considered as definitive for further calculations.

The complete composition of the mixture is determined with the parameter $(CO)/n = 0.172$ and Fig. 5 (Graph B).

$$(CO) = 0.172 \times 6 = 1.032$$
$$(CO_2) = 6 - 1.032 = 4.968$$
$$\frac{(O_2)}{V} = 5.67 \times 10^{-5}$$
$$(O_2) = 5.67 \times 10^{-5} \times 7.470 = 0.424$$
$$(O) = 5 \times 10^{-6} \times 7470 = 0.03735$$
$$\frac{(NO)}{k}\sqrt{\frac{k}{V}} = 2.63 \times 10^{-4}$$
$$(NO) = 0.170$$
$$(N_2) = \frac{56.4 - 0.170}{2} = 28.115$$
$$\frac{(H_2)}{m} = 1.6 \times 10^{-2}$$
$$(H_2) = 1.6 \times 10^{-2} \times 6 = 0.096$$
$$(H) = 1.13 \times 10^{-3}\sqrt{(H_2)}\sqrt{V} = 1.13 \times 10^{-3}\sqrt{0.096 \times 7470} = 0.0304$$
$$\frac{(OH)}{(H_2O)} = \frac{1.745 \times 10^{-4}\sqrt{V}}{\sqrt{(H_2)}} = 1.745 \times 10^{-4}\sqrt{\frac{7470}{0.096}} = 0.0488$$
$$(H_2O) = \frac{m - 2(H_2) - (H)}{2 + [(OH)/(H_2O)]} = 2.82$$
$$(OH) = (H_2O) \times \frac{(OH)}{(H_2O)} = 2.82 \times 0.0488 = 0.1380$$

The equilibrium constants are verified with the calculated partial pressure within 3 per cent, and the mass balance equations within 1 per thousand.

It will be noticed that the composition point lies within the useful portion of Fig. 6 (Graph C) so that it is possible to verify the value $(H_2O)/m = 0.47$, or $(H_2O) = 0.47 \times 6 = 2.82$ found before by another method.

II *Mixture composition of the combustion products of benzene in air (f/a, equivalence ratio = 1.1) at T = 2400 K and P = 1 atm:*

The combustion equation

$$1.1C_6H_6 + 7.5O_2 + 28.2N_2 = (CO_2)_0 + (CO)_0 + (H_2)_0 + 28.2N_2$$

gives the numerical values of the different parameters $n = 6.6$, $m = 6.6$, $l = 15$, $k = 56.4$.

In order to get the first approximation, it can be assumed that the second member of the combustion is related to the water gas equilibrium, but it is not necessary to write this equation for $(CO_2)_0 + (CO)_0 = n$ and $(H_2O)_0 + (H_2)_0 = m/2$.

Finally the number of moles is $\Sigma_0 = n + (m/2) + (k/2) = 6.6 + 3.3 + 28.2 = 38.1$ and $V_0 = [(38.1 \times 0.0821 \times 2400)/1] = 7500\ m^3$.

The line $a = [(l - 2n)/m] + (n/m)[(CO)/n]$ with the numerical values takes the following form: $a = 0.273 + [(CO)/n]$.

The intersection of this line with the curve $V_0/m = 7500/6.6 = 1135$ is given by the coordinates $(CO)/n = 0.256$ and $a = 0.529$. As previously, Fig. 5 (Graph B) gives $(NO)/k\sqrt{k/V} = 1.6 \times 10^{-4}$ and $(NO)/m = 1.73 \times 10^{-2}$, and Fig. 6 (Graph C) the value $\sigma H/m = 0.585$.

The new number of moles

$$\Sigma = 6.6 \times 0.585 + 6.6 + \frac{6.6 \times 1.73 \times 10^{-2} + 56.4}{2} = 38.72$$

and the new volume $V = 7620$ correspond to the second approximation related to the intersection point of the line, $a = 0.273 - 0.0173 + (CO)/n$, with the volume curve $V/m = 1155 m^3/H$. Its coordinates are $(CO)/n = 0.267$ and $a = 0.523$. The accuracy of these results can be considered sufficient for the further calculation of different components:

$$(CO) = 1.76$$
$$(CO_2) = 4.84$$
$$\frac{(O_2)}{V} \text{ (Fig. 5, Graph B)} = 1.74 \times 10^{-5} \text{ and } (O_2) = 0.14$$
$$\frac{(O)}{V} \text{ (Fig. 5, Graph B)} = 2.85 \times 10^{-6} \text{ and } (O) = 0.0217$$
$$\frac{(H_2)}{m} \text{ (Fig. 5, Graph B)} = 2.75 \times 10^{-2} \text{ and } (H_2) = 0.181$$
$$(H) = 1.13 \times 10^{-3}\sqrt{0.181 \times 7620} = 0.042$$
$$\frac{(OH)}{(H_2O)} = 1.745 \times 10^{-4}\sqrt{\frac{7620}{0.181}} = 0.0358$$
$$(H_2O) = \frac{6.6 - 0.362 - 0.042}{2 + 0.358} = 3.04$$
$$(OH) = 3.04 \times 0.0358 = 0.109$$
$$(NO)\sqrt{k/V} \text{ (Fig. 5, Graph B)} = 1.5 \times 10^{-4} \text{ and } (NO) = 0.0985$$
$$(N_2) = \frac{56.4 - 0.0985}{2} = 28.15$$

III *Composition of the combustion products of methane in oxygen (lean mixture, equivalence ratio 0.8) at T = 2400 K and P = 10 atm:*

From the combustion reaction

$$0.8CH_4 + 2O_2 = 0.8CO_2 + 1.6H_2O + 0.4O_2$$

one can express the numerical values of different parameters as $n = 0.8$, $m = 3.2$, $l = 4$, $k = 0$, the initial total number of moles $\Sigma_0 = 2.8$, and the initial volume $V_0 = [(2.8 \times 0.0821 \times 2400)/10] = 55.1 m^3$.

With these values the intersection point of the line $a = [(l - 2n)/m] + (n/m)[(CO)/n]$ or $a = 0.75 + 0.25[(CO)/n]$ with volume curve $V_0/m = 55.1/3.2 = 17.2$ has the following coordinates: $(CO)/n = 0.018$, $a = 0.754$. $\sigma H/m$ necessary for the evaluation of the total number of molecules is read on Graph C (Fig. 6) and equals 0.63. This value introduced in the equation of the actual total number of moles, $\Sigma = m(\sigma H/m) + n = 3.2 \times 0.63 + 0.8 = 2.81$ shows a very small variation of the last number. So this point can be considered as definitive. As the composition point lies within the portion of the plane determined by the condition $(CO)/n < 0.1$ and $a > 0.6$, it is advantageous in order to get better accuracy to operate with the method described as a particular case (sect. i under "Particular Cases," p. 113).

Fig. 7 (Graph D) used in this method gives $(O_2)/m = 0.127$, or $(O_2) = 0.407$ with $a = 0.754$.

The atomic oxygen is immediately calculated from the relation $O = 6.68 \times 10^{-4}\sqrt{V \times (O_2)} = 6.68 \times 10^{-4}\sqrt{55.1 \times 0.407} = 0.00316$ as well as the ratio $(CO_2)/(CO) = 6.41 \times 10^2\sqrt{(O_2)/V} = 6.41 \times 10^2\sqrt{0.407/55.1} = 55$.

The corresponding (CO) is determined by the equation $(CO) = \{n/[1 + (CO_2)/(CO)]\} = 0.8/56 = 0.0143$.

Fig. 6 (Graph C) is available for the evaluation of all hydrogen compounds; it indicates $(H_2O)/m = 0.494$ and $(H_2O) = 0.494 \times 3.2 = 1.58$. Taking into account these values, all other compounds are successively determined using the following relation:

$$(H_2) = 0.164\frac{(CO)}{(CO_2)} \times (H_2O) = \frac{0.164 \times 1.58}{55} = 0.0047$$
$$(H) = 1.13 \times 10^{-3}\sqrt{0.0047 \times 55.1} = 0.000575$$
$$\frac{(OH)}{(H_2O)} = 1.745 \times 10^{-4}\sqrt{\frac{55.1}{0.0047}} = 1.89 \times 10^{-2}$$
$$(OH) = (H_2O)\frac{(OH)}{(H_2O)} = 1.58 \times 1.89 \times 10^{-2} = 0.0299$$

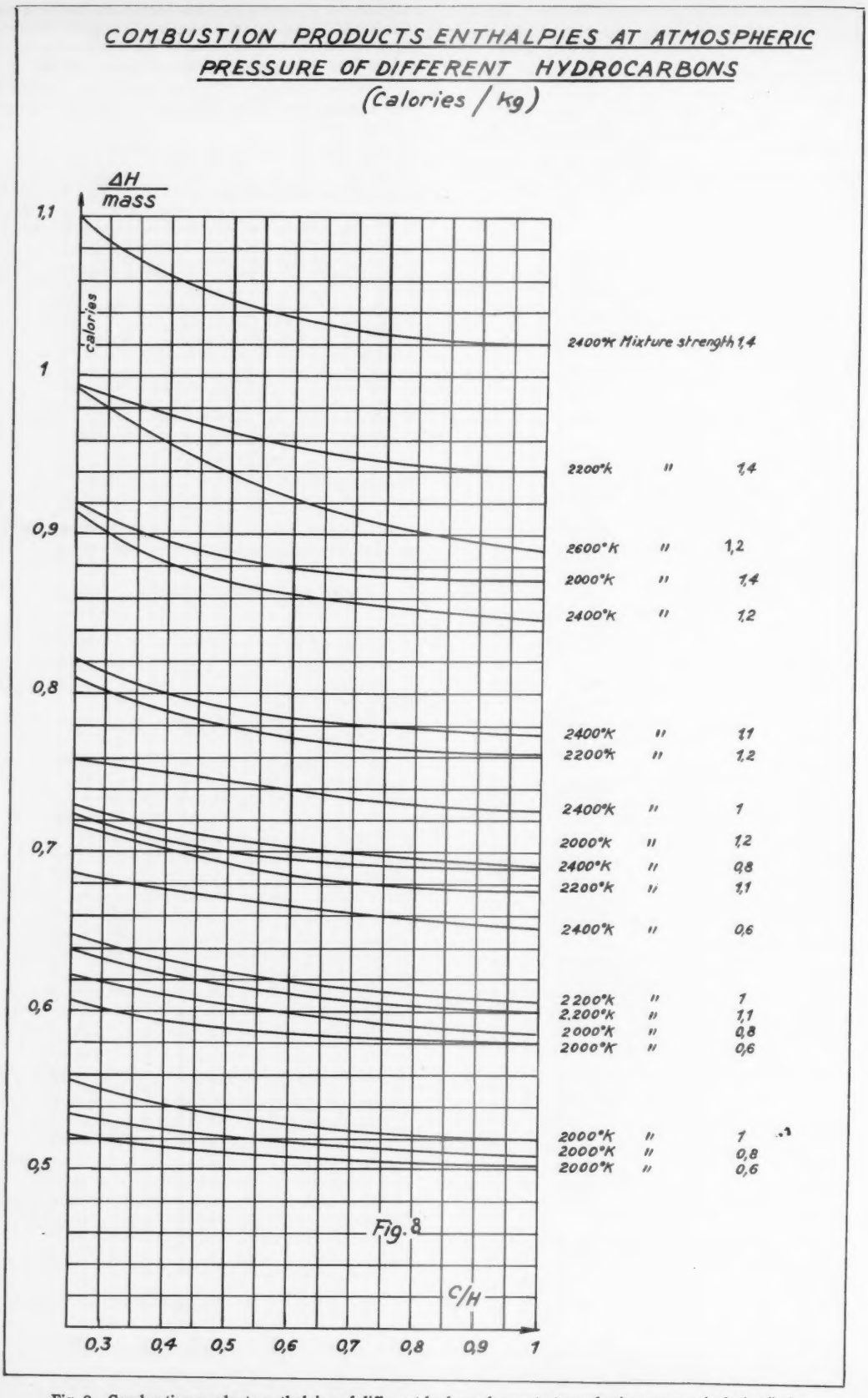

Fig. 8 Combustion products enthalpies of different hydrocarbons at atmospheric pressure (calories/kg)

These three illustrative examples for different equivalence ratios show that it is quite possible to calculate the composition of the combustion products with a high accuracy without use of complicated electronic or mechanical computers in less than fifteen minutes.

C Combustion Temperature of Hydrocarbons in the Air at Atmospheric Pressure

The theoretical calculation of combustion temperatures has only a means when the experimental data are able to confirm them. But in many cases where the experimental determinations are tedious, these calculations representing a first approximation are useful for the resolution of industrial problems relative to flame radiation, flame speed, etc.

The speed of flame propagation of hydrocarbons burning in air was measured at atmospheric pressure with sufficient accuracy. Some attempts were made to build new theories of flame propagation based on the assumption of the diffusion of free radical, or on the chain reactions, for the conductivity theory was inadequate to explain the particularities of this phenomenon. Whatever the theory considered, the temperature of combustion remains one of the most important factors. Unfortunately the calculations of temperature and gas composition in numerous papers were restricted to one particular value of the mixture ratio corresponding to the maximum speed of the flame. In some other cases the theories were established for one kind of hydrocarbon. It seems that the difficulties of calculations have limited the field of investigation.

The purpose of the following section is to give the combustion temperature of most of the hydrocarbons in air at atmospheric pressure, for which the flame propagation speeds were measured in a large range of mixture ratios.

Process of Operation

As the combustion equation for each hydrocarbon at a given mixture strength is given by the C/H ratio, five different values of this ratio between 0.25 and 1 (methane C/H = 0.25; benzene C/H = 1) are sufficient to represent the combustion products in the air of most hydrocarbons. The previously described method was used to calculate the gas composition at temperatures 2000, 2200, and 2400 K for the following mixture equivalence ratios: 0.6, 0.8, 1, 1.1, 1.2, and 1.4.

The second step of calculation is the evaluation of the total enthalpy of the combustion products; for this, the energy of formation at the reference temperature was added to the enthalpy of the products. For instance, in the case of methane (rich mixture, 1.2), the following results are reported in Table 6.

Table 6 Enthalpy of Combustion Products of Methane at 2400°K and P = 1 atm

Products	Number of moles	Energy of formation	Enthalpy of components
CO	0.5352	36.200	9.120
CO_2	0.6348		18.180
O_2	0.0081		0.145
O	0.0029	0.176	0.030
H_2	0.2784	16.100	4.460
H	0.0264	2.140	0.275
H_2O	2.1400		48.000
OH	0.0355	1.585	0.574
NO	0.0125	0.270	2.217
N_2	7.5000		127.200
		56.471 Kcal	210.201 Kcal
		Total enthalpy:	266 672 Kcal

Auxiliary graphs of enthalpy for different mixtures were represented versus C/H ratio. Such representation with the temperature as second parameter is most valuable. Another chart, the H-t diagram of Le Chatelier, was deduced from the preceding one with C/H as parameter (C/H = 0.25, 0.3, 1). For lean mixtures it was necessary to establish a set of such charts, since the same value of enthalpy can be found for two different mixtures with two different C/H ratios. Using this auxiliary chart the combustion temperature of a hydrocarbon is easily computed when the lower heat of combustion, the mixture ratio, and the ratio C/H are known.

The lower heat of combustion permits the evaluation of the available energy which will be employed to bring the final products from the reference temperature to the combustion temperature. For instance, as the lower heat combustion of benzene is 757 Kcal per mole, the chemical energy for the mixture corresponding to the combustion equation, $1.2C_6H_6 + 7.5O_2 + 28.2N_2$, will be equal to 1.2×757 Kcal or, reported to the unit of mass, 0.810 Kcal/g.

The intersection of the parallel to the abscissa of ordinate 0.810 with the curve $H = f(T)$ (Fig. 8) determined by parameters mixture ratio = 1.2 and ratio C/H = 1, immediately gives the required solution. In the range of lean mixtures the chemical energy is less than that at stoichiometric mixture.

In Fig. 9 there are reported the temperatures calculated by this method for the different hydrocarbons. It can be assumed, taking into account the precision of the thermodynamic data, that the accuracy on the temperatures values is about ±5 K. This figure calls for some remarks.

1 The highest temperatures are realized with the acetylenic hydrocarbons and the lowest with the isoparaffins.

2 The combustion temperature difference of homologous hydrocarbons of the paraffinic and isoparaffinic series is rather small.

3 The cycloparaffins have higher combustion temperature than paraffins with the same number of carbons.

4 A difference of combustion temperatures of at least 50 K was found between paraffins and aromatics, olefins, and diolefins.

5 At atmospheric pressure, the maximum temperature is obtained with mixtures richer than the stoichiometric one and particularly rich for the acetylenic series.

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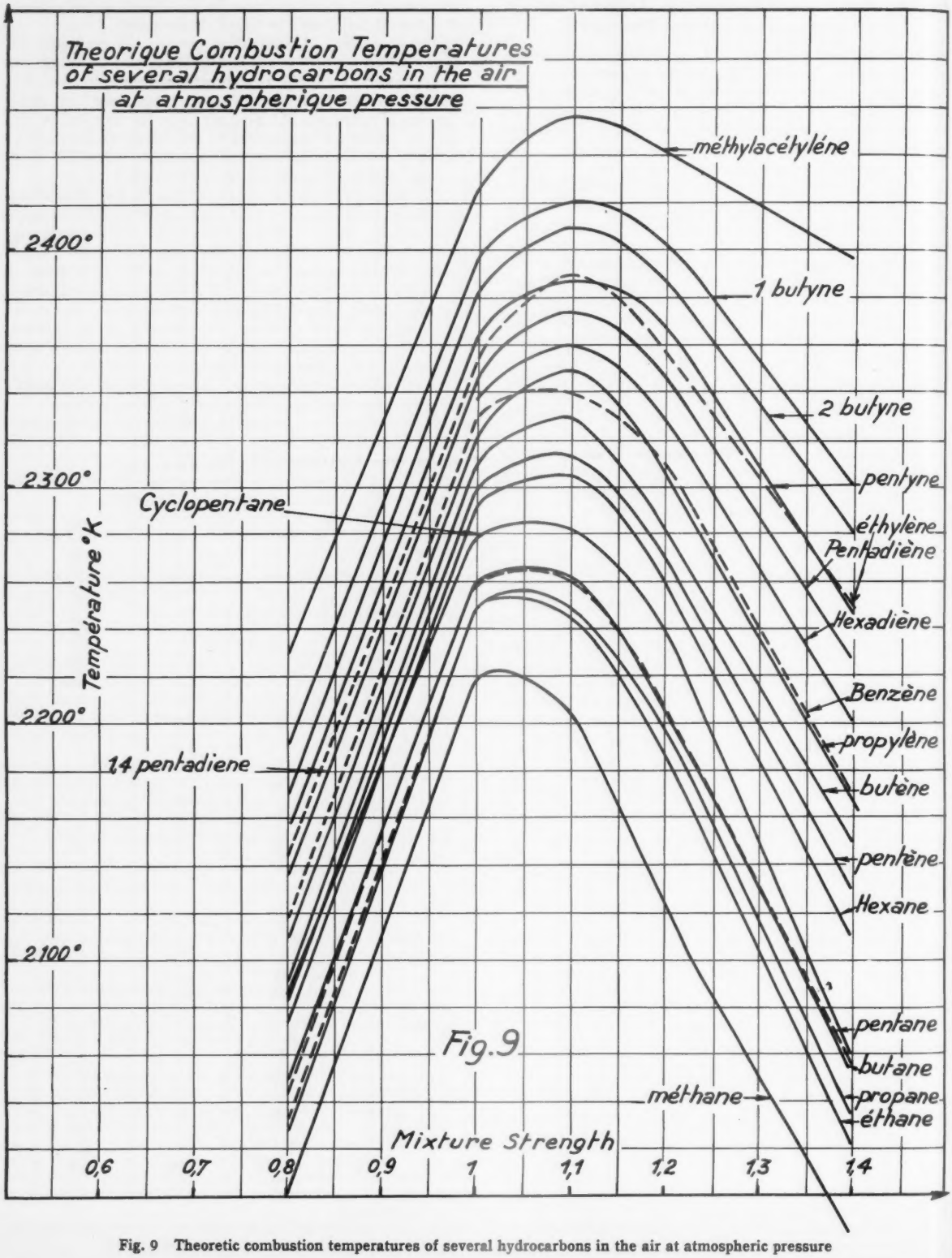

Fig. 9 Theoretic combustion temperatures of several hydrocarbons in the air at atmospheric pressure

Indicated Instantaneous Temperatures of Liquid Rocket Exhausts and Combustion Chambers[1]

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A modified two-path method was used to measure indicated instantaneous temperatures of the exhaust and combustion chamber flames of 1500-lb-thrust alcohol-oxygen rockets. Spectral studies of the flames indicated divergence from thermal equilibrium in both combustion chamber and exhaust. Nevertheless the indicated temperatures obtained agreed closely in the exhaust flames with average temperatures obtained by the method of Kurlbaum, but were lower than average temperatures obtained by the sodium line reversal method. The measured temperatures in the combustion chamber and the exhaust were lower than the theoretical temperatures.

I Exhaust Temperatures

IN THIS paper a report is made of some instantaneous temperatures determined at the exhaust and at the combustion chamber of a 1500-lb-thrust alcohol-oxygen rocket. This work was done at the Malta Test Station of the General Electric Company through their co-operation and with the co-operation of Army Ordnance. The project was financed by Project Squid, Office of Naval Research. Actual observations were taken at regular periods from January 1950 to August 1951. The work included considerable spectrographic study of the flames, since it was by no means a priori certain that temperature had meaning in the rocket flames, where it is well known that the gas is highly turbulent and contains pockets of unburned vapors and droplets, reaction zones and combustion products of gases.

The temperature measuring instrument used here averages the temperatures along the line of sight through the nonuniform flame. There is as yet no optical method of obtaining the temperature solely at a point or in a very small region in the flame.

Instantaneous temperatures have been obtained for other type flames by others; for example: R. S. Craig (1)[3] used a two-color path measuring temperatures of solid propellant rocket combustion. S. J. Jacobs and T. P. Cotter (2) used a variation of the two-color method to determine the temperature in detonating explosives. In the field of rockets the most consistent study of exhaust temperature measurements, though integrated over many seconds of time, is that of H. M. Strong and F. P. Bundy (3) who used the sodium line reversal method. Some time after the work on this paper was completed, Heidmann and Priem (4) reported temperatures in flame tubes using rocket fuels.

Apparatus Used

The temperature instrument was the New York University instantaneous pyrometer (5) which was mounted in No. 1 firing pit of the Malta Test Station. The theory of this instrument is as follows: It was shown by A. Schack (6) that the radiation in the continuous background of the spectrum of a hydrocarbon flame is in thermal equilibrium with the gas. If one utilizes for temperature measurement a region of this spectrum which is free from line and band structure, one can avoid all questions concerning line form and resolution, whether the radiation producing the line is actually in thermal equilibrium with the gas, and the relation of line intensity to background intensity. Such considerations led the writers to develop the following method of measuring instantaneous temperatures averaged over the line of sight. Light which is emitted from the flame is focused by a lens on a photocell through a filter forming light path 1. The same lens focuses a mirror located behind the flame through the same filter on a second photocell forming light path 2. In this way, by recording the light intensities of both paths, both instantaneous temperatures and emissivities of the flame may be inferred. Spectral studies of the rocket showed higher energies in the blue region and lower energies in the red region than Planck's law would allow. However, by selecting carefully the spectral region, we may obtain "indicated temperatures." We assume for the purpose of analysis that the temperature to be measured is defined by Planck's radiation law and that the absorption is given by the usual negative exponential function appearing in Equation [1] below.

In some experiments with pulsejets in which some additional light was scattered into the radiation cone observed by the radiation pickup, the effect was too small to be measured, and hence scattering effects are neglected. For the purpose of this paper, polarization and diffusion effects are also neglected.

If we assume that the various kinds of molecules giving rise to the continuous background are in thermal equilibrium with the kinetic temperature, then the spectral intensity observed from a slab of gas, of thickness L extending from $x = 0$ to $x = L$, is, per unit area

$$I_L = \int_0^L \exp\left[- \int_0^x \sum_n k_n(v, T(x)) \cdot \rho_n(x)\, dx \right] \times I_B(v, T(x)) \sum_n k_n(v, T(x)) \cdot \rho_n(x)\, dx \quad [1]$$

at frequency v, where $k_n(v, T(x))$ = absorption coefficient per unit mass where temperature is $T(x)$; $\rho_n(x)$ = density at point x at which temperature is $T(x)$; $I_B = 2hv^3/c^2\,(e^{hv/kT(x)} - 1)$ intensity of black body at temperature $T(x)$ according to Planck's relation.

It will be noted that in the above integral the actual conical shape of the observed radiation region is not explicity taken into account, but the complete equivalence of this configuration to the simple cylindrical region assumed here can be easily shown.

If in Equation [1] for all molecules giving rise to the radiation, the instantaneous temperatures and densities are considered approximately uniform throughout the region, then at

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[1] This work was undertaken as a co-operative program of fundamental research in jet propulsion for the Office of Naval Research, Department of the Navy, and the Office of Air Research, Department of the Air Forces under Contract N6ori-11, Task Order II, NR 220-040, Project SQUID.

[2] Research Associates, Research Division.

[3] Numbers in parentheses indicate References at end of paper.

the frequency under consideration the sum $\sum_n k_n(\nu, T \cdot (x)) \cdot \rho_n(x)$ can be replaced by the sum $\sum_n k_n \rho_n$ which in turn can be denoted by a constant β.

If light from path 1 is transmitted through a window of transmission coefficient, γ, then the resulting intensity as seen at the photocell is, after integrating [1],

$$I_L' = I_B\gamma\,(1 - e^{-\beta L}) \quad \ldots\ldots\ldots\ldots\ldots\ldots [2]$$

Under the same circumstances with a mirror at $x = L$, with reflection coefficient R, the intensity observed on viewing the second path is

$$\left.\begin{aligned} I_L'' &= I_L' + R\gamma^3 I_B \int_L^{2L} \exp\left(-\int_0^x \beta\,dx\right)\beta\,dx \\ I_L'' &= I_L' + R\gamma^3 I_B e^{-\beta L}\,(1 - e^{-\beta L}) \end{aligned}\right\} \quad \ldots\ldots [3]$$

Equations [2] and [3] contain two unknowns, β and I_B. Solving for I_B, we obtain

$$I_B = I_L'^2 R\gamma/(I_L' R\gamma^2 + I_L' - I_L'')$$

Electronic Circuits

The electronic circuits used for the exhaust work were essentially the same as had been used in pulsejet investigation. They are described in detail in Reference (5).

The photocell pickups were 1P21 photomultipliers. A 6C4 cathode follower matched the impedance of the photocell load to that of the coaxial cable running to the d-c amplifier. For pulsejet work, a 10k resistor had been used in conjunction with the capacity of the cable to provide a low band pass filter so that noise components above 6000 cps were eliminated.

The rocket exhaust flame was found to be so bright that it was possible to operate the photomultipliers at very low voltage settings and thus eliminate the tube noise at its source. The 6000-cycle band pass filter was removed.

The signal was fed into a conventional push-pull d-c amplifier which had a variable gain ranging from 300 to about 3000. The amplifier was usually operated close to its low gain setting.

For the combustion chamber work a different d-c amplifier was used. This one had a variable gain ranging from zero to about 1000. The simplicity and stability of this amplifier was a considerable improvement over the earlier model. The improvement was obtained chiefly by eliminating one stage of amplification and using miniature tubes. A twin triode 12AT-7 replaced the two 6SJ7s formerly used as the balanced output stage.

For the exhaust work, this instrument was mounted 10 in. downstream from the rocket nozzle. The mounting was made adjustable so that the optical axis of the instrument, which was normal to the exhaust, could be easily moved up or downstream and in a vertical plane to observe any chord of the exhaust. Observations could not be made within several inches of the exhaust orifice because the instrument would have restricted the view of the pit operator. Recording equipment was mounted in the control room of the pit, and vibration was not a problem.

The spectroscopic work was done with a Hilger spectrographic camera, focal length 21 in., dispersion 67 Å/mm at 6000 Å. This instrument was mounted in an observation cell above the first Mach cone. Its field of view was about 12 in. adjusted to sight the Mach cone. The slit of the spectrograph was set at right angles to the rocket axis. Tri-X plates $3^1/_4 \times 4^1/_4$ in. were used. These plates were measured with a Marshall densitometer which is an inverse square device utilizing a brightness match in the apparent field.

High-speed motion pictures of the exhaust were taken with a Fastax 16-mm camera run at 3600–4800 frames/sec. The field of view was about 2 ft, including the first Mach cone. The camera was mounted in the overhead observation cell.

Exhaust Flame Observations

The spectrograph showed the exhaust flame to be a strong continuum with the NaD line and the 5165 and 4382 (C2) band heads superposed. It was decided to try the NYU temperature instrument on the assumption that the continuum was in thermal equilibrium. The later spectrographic reductions showed that the rocket radiation both from the exhaust and in the chamber is not truly Planckian and hence the temperatures recorded should be considered as merely indicated temperatures.

The temperature instrument was originally set to sight through the first Mach cone, and later in the investigation was set to sight through the flame 2 in. in front of the leading tip of the Mach cone. Farrand interference filters of 150 Å, or less half width, centered at 5720 Å were originally used. This region of the spectrum appeared on the plates to be a continuum free of irregularities. Reduction of the temperature records showed an apparent temperature through the first Mach cone in the neighborhood of 1650 K, later reduced to an indicated true temperature of 1900 K. A more precise determination by Kurlbaum's method (described later in this paper) showed the emissivity to be about 0.15 at 5310 Å.

Several rocket runs gave consistent readings in the temperature range of 1900 K. These results were lower than had been expected and lower than the temperatures measured by Bundy and Strong using a line reversal method. It was accordingly decided to take measurements in different spectral intervals. Red and blue-green filters centered at 6100 and 4830 Å, respectively, were used. These regions were also a substantially clear continuum. A group of readings with the red filter gave an average apparent temperature of 1600 K with the instrument sighted through the Mach cone. Readings taken with the blue-green filter under the same conditions gave an average temperature of 1850 K for the Mach cone.

In view of this dependence of measured temperature on wave length, it was decided to study further the character of the rocket radiation to determine particularly what deviations from the Planckian curve might be expected. When this was done, as reported later, it was found that the blue-green region had a higher emissivity than the red region.

A typical pair of radiation traces for a G-E 1500-lb rocket is given in Fig. 1. Irregularities shown had a high frequency and small amplitude. High-speed motion pictures were taken of the Mach cone which showed that the cone actually presents a very streaky appearance due to turbulence and streamers of cooler gas passing through it. It is possible that these streamers account for the small irregularities in some of the radiation traces recorded. Fig. 2 shows the face of the oscilloscope with calibration marks. Fig. 3 shows a rocket being run at reduced pressure just before shutdown and consequently "beating." Frequency of oscillation is 206 per sec. The temperature variation is approximately 150 K.

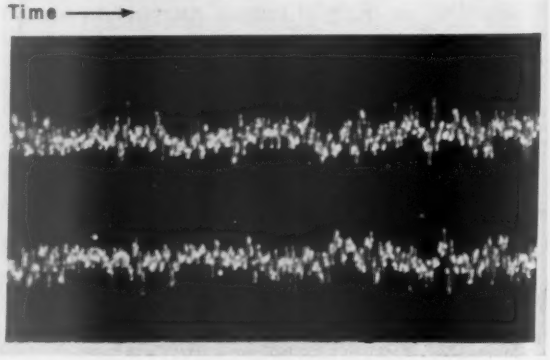

Fig. 1 GE run no. 2131 M1 4830 Å filter. Temperature oscillations 50 K peak to peak

Table 1 Summary of exhaust temperature observations

Run no.	Date (1950)	Fuel oxidizer mixture ratio	Combustion chamber pressure, psig	Filter, Å	Location	Film speed, in./sec	Indicated $T°$ K	Remarks
2081 M 1	3/28 1:25 p.m.	1.39	380	6100	Inside Mach cone	40	Max.—1953 K	Poor record
2084 M 1	3/29 10:20 a.m.	1.52	369	6100	2 in. ahead of tip of Mach cone	40	Max.—1655 K Min.—1595 K	Zero, drifted Good record
2085 M 1	3/29 10:45 a.m.	1.35	373	6100	2 in. ahead of tip of Mach cone	30	Max.— Min.—1575 K	Poor record
2091 M 1	3/31 11:00 a.m.	1.36	368	6100	Tip of Mach cone	40	Max.—1687 K Min.—1662 K	Poor record
2092 M 1	3/31 11:30 a.m.	1.34	368	6100	Tip of Mach cone	40	Max.—1720 K Min.—1630 K	Good record
2129 M 1	4/20 10:55 a.m.	1.26	452	4830	Just inside Mach cone	40	Max.—2121 K Min.—1969 K	Good record
2131 M 1	4/20 2:00 p.m.	1.75	448	4830	Just inside Mach cone	40	Max.—2146 K Min —2098 K	Good record

The summary of indicated temperature observations using an emissivity of 0.15 determined by the Kurlbaum method is given in Table 1. Since the results given in Table 1 show a dependence on the spectral region observed, it was essential to study further the spectral energy distribution of the rocket. Further, Bundy and Strong observing a similar rocket, determined by the sodium line reversal method an integrated temperature along the line of sight through the first Mach cone of 2360 K, where we show temperatures of about 2130 K. It was hoped that the study of the spectra would resolve this difference; but since the spectra turned out to be largely non-Planckian, no strict determination could be made.

Spectrographic Data

Spectroscopic plates were initially taken of the exhaust to determine the position of line and band structures so that the filters chosen would pass only the continuous background. As the work developed, it became increasingly important to study the equilibrium characteristics of the background radiation. These plates, though originally taken for qualitative observation, were reduced to determine the spectral energy distribution. Though the development process had not been rigidly controlled, subsequent sensitometric investigations showed negligible error due to processing. Though ten spectra were taken of the rocket exhaust, the runs were often so short in duration that sufficiently dense spectra for quantitative analysis were achieved on only six plates. Typical spectrographs of the rocket exhaust are shown in Figs. 4, 5, and 6. The rocket exhaust plates were reduced by the following method: (The plates of the combustion chamber flame taken in Phase 2 of the studies were reduced by a different technique, discussed in section II).

1 Film characteristic curves were obtained for different developers and different exposure times. As long as the densities were low, which was true for all the exhaust spectra, these variables were negligible.

2 The emulsion was exposed to a gray scale using white light as a control and then successively exposed with the red, yellow, and blue interference filters over the light source. The exposure time for each filter was adjusted so that all the gray scales had equal densities at their densest step. This enabled one to make a correction for difference in contrast for the various colors.

3 A color sensitivity curve for the emulsion was obtained from a wedge spectrogram supplied by Eastman Kodak. This gave the response of the emulsion to a spectrum of a tungsten source at a known temperature. It was necessary to correct this wedge spectrogram for the wave-length dependence of the emissivity of the tungsten lamp at selected temperatures.

4 After the appropriate corrections were made for color sensitivity, the next step was to correct for the nonlinear dispersion of the spectrograph.

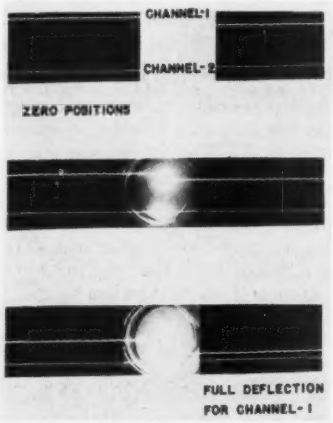

Fig. 2 Typical calibration record, showing the deflection of one of the cathode-ray spots due to various amperage settings of the strip calibration lamp. In operation, each channel is calibrated in turn. This figure shows the deflection and hum level for six different amperage settings for channel no. 1. The spots deflect toward the center of the cathode-ray tube face for increasing light signal. The face of the tube is photographed by the diffused light from the cathode-ray spots when the film in the recording camera is halted during a change in amperage setting

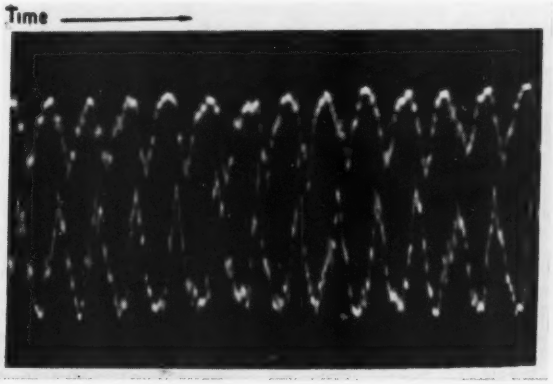

Fig. 3 North American Rocket radiation traces. Rocket is being run at reduced pressure, just before shutdown. Frequency of oscillation is 206 cps GE run 2023 M1

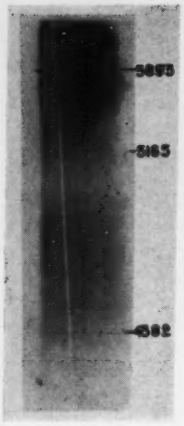

Fig. 4

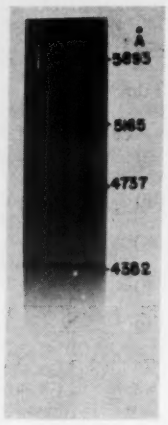

Fig. 5

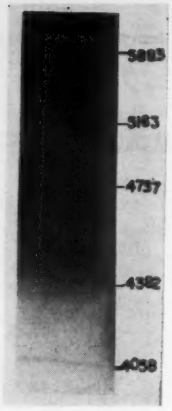

Fig. 6

Fig. 4 The spectrum of the first Mach cone. Ethyl alcohol and oxygen. GE run 2068 M1. Exp. 20.5 sec. Tri-X Pan. The enhanced density to violet of NaD line is largely a plate characteristic. This spectrogram is characteristic of most runs

Fig. 5 The spectrum of the first Mach cone. Ethyl alcohol and oxygen. GE run 2076 M1. Tri-X Pan. This spectrum clearly shows the C_2 band heads and many of the component lines

Fig. 6 The spectrum of the first Mach cone. Ethyl alcohol and oxygen plus tetraethyl lead (20 cc/gal). GE run 2063 M1. Exposure 2.5 sec. Tri-X Pan. This spectrum also shows the C_2 lines and in addition some lines probably due to lead oxide. The line at 4058 is due to atomic lead

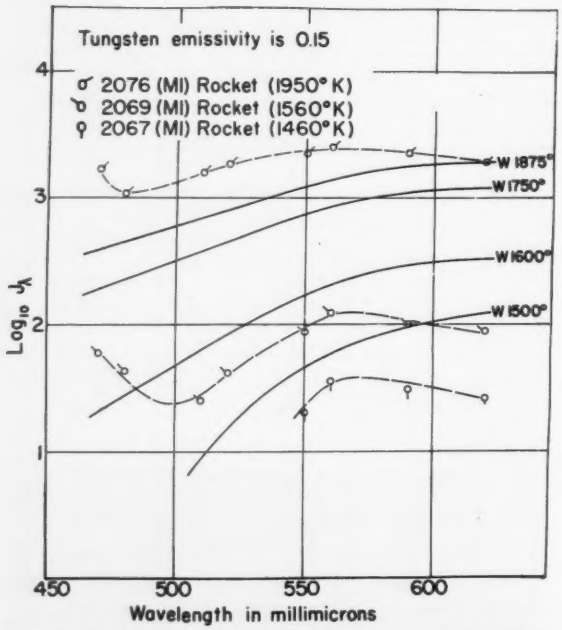

Fig. 7 Plots of $\log_{10} J_\lambda$, the energy from Planck's radiation law versus wave length, for tungsten strip lamps as observed through NYU spectroscope. Tungsten curves are plotted for over-all emissivity of 0.15 and arbitrarily adjusted in ordinate at 6200 Å. The true scattering and absorption of the tungsten curves are unknown. Three rocket curves are plotted into this field by matching of rocket slopes in the central spectral region. Thus, temperatures are determined for the rockets giving some check on Table 1. Run no. 2076 just downstream from tip of first Mach cone. Run no. 2069 just downstream from tip of first Mach cone. Run no. 2067: Region includes downstream half of first Mach cone and some of the interspace to second Mach cone

As a check on the above methods and as a means of determining the instrumental errors, chiefly absorption and scattering effects, these techniques were applied to spectrograms of the tungsten strip calibration lamp, taken in the laboratory. The solid lines in Fig. 7 show the shape of the observed energy curves of the strip lamp for various temperatures reduced to an over-all emissivity of 0.15, and arbitrarily adjusted to true gray-body curves at 6200 Å. These curves then contain all the instrumental errors. As the temperatures of the tungsten curves drop, their slopes in the violet become steeper than the Planckian curves. This is probably due to errors of measuring at the foot of the H and D curves. However, no final error is introduced into the temperatures since the rocket curves were reduced consistently. Also, all the rocket curves show some flattening above 5650 Å.

Reduction of Rocket Spectra

Three of the six good spectrograms of the rocket exhaust were reduced by the above-outlined 4-step method. Since the density of spectrograms is a function of spectroscope slit width, time of exposure, and emissivity of flame, it is not possible to compare spectra directly against each other. Thus, for any one spectrum, the reduced intensities were plotted against wave length starting with some arbitrary ordinate at 6200 Å. These curves were then moved in ordinate over the corrected strip lamp curves of Fig. 7 and the rocket temperature derived by matching the slope of the rocket curve with the strip lamp curves.

Fig. 7 shows the plot of three rocket runs superposed on the background of the tungsten curves. If the rocket curves were pure Planckian, they would be expected to fall along sets of curves similar to the tungsten curves, since the slopes of the tungsten curves have already been corrected for instrumental errors. The rocket curves have been plotted in Fig. 7 without correcting for the emissivity of the rocket. Since, however, we have evidence from Kurlbaum's method that the rocket emissivity is 0.15, and since the tungsten curves are plotted for emissivity 0.15, the positions of the rocket curves yield true "indicated temperatures."

Fig. 7 also shows clearly that the rocket spectra are more intense than gray-body radiation below 4800 Å and less intense above 5650 Å.

It is indicated in Table 1 that the measurements taken with the temperature instrument showed a wave-length dependence. Measurements made with the blue 4830 Å filter gave temperature readings consistently higher than those obtained from the same sort of flames using longer wave-length filters, such as the 6100 Å filter.

Temperature and Emissivity from Kurlbaum's Method

To obtain an independent check on the *average* temperature and emissivity the following method, originally devised by Kurlbaum, was used. The optical sighting system of one channel of the NYU apparatus was sighted through the flame to an effective black body, the strip lamp, whose temperature could be varied.

If the flame is a gray-body emitter, the strip lamp brightness may be adjusted until the brightness of the strip seen through the flame is the same as when sighted upon directly. Under this condition, the temperature of the lamp is the same as that of the flame. This is evident from the following equation:

$$c_1\lambda^{-5}\, e^{-(c_2/\lambda T_0)} = kc_1\lambda^{-5}\, e^{-(c_2/\lambda T_1)} + c_1\lambda^{-5}\, e^{-(c_2/\lambda T_0)}(e^{-\alpha L})$$

Radiation from black-body source = Radiation from flame + Radiation from black-body source partially absorbed by flame

where

T_0 = true temperature of black body
T_1 = true temperature of flame
k = emissivity of flame $= (1 - e^{-\alpha L})$
α = absorption coefficient of flame
L = thickness of flame

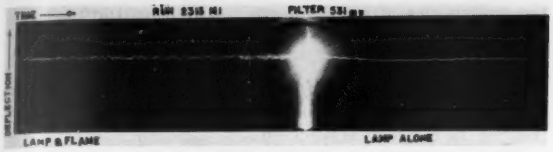

Fig. 8 Brightness match between lamp and flame plus lamp at 1900 K

Fig. 9 The ratio of the two signal strengths determined from the above record gives the emissivity of the flame for the spectral interval used

Two runs, nos. 2315 and 2318, were taken on December 13 and 14, 1950, using alcohol-oxygen. Both were taken about 2 inches downstream from tip of Mach cone.

A filter 150 Å wide was used, centered at 5310 Å.

Fig. 8 shows how the lamp brightness matches the lamp plus flame. The indicated average temperature was found to be 1900 K ± 50°.

Fig. 9 shows a record used to determine the emissivity. The left part of the curve is the signal from flame plus strip lamp, and is a deflection equivalent to 10.6 amp through the lamp, or 1900 K. The deflection produced by the flame alone is equivalent to a signal from a strip lamp setting of 9.0 amp, or 1675 K. From the equation

$$c_1 \lambda^{-5} e^{-(c_2/\lambda T_{app.})} = k c_1 \lambda^{-5} e^{-(c_2/\lambda T_{true})}$$

solving for emissivity k

$$k = e^{\frac{1.433}{5300\ \text{Å}}\left(\frac{1}{1900} - \frac{1}{1675}\right)}$$
$$= 0.15 \pm 05$$

II Measurement of Indicated Instantaneous Temperatures in a Liquid Fuel Rocket Combustion Chamber

This part of the report covers indicated temperatures of the rocket combustion chamber using the same temperature measuring instrument as indicated in section I. Work was also done at the Malta Test Station of the General Electric Company. A 3-in.-diam 1500-lb-thrust alcohol-oxygen rocket was used for these tests.

Window Design

The windows were mounted diametrically opposed on a 3-in.-diam G-E rocket motor combustion chamber as shown in Fig. 10. The rocket with the windows was given an initial 10-sec test run on March 10, 1951. The rocket ran successfully and the windows were found to be in excellent condition at the end of the run. The rocket has been run some 38 times with runs up to 20 seconds in duration.

Fig. 11 shows top, bottom, and exploded view of a window assembly. The window is made of fused quartz polished flat to four bands across the face. The O-rings are silicon rubber; the metal parts are stainless steel except for two brass washers shown one on each side of the quartz cylinder at the right-hand side of Fig. 11. The washers serve to position the quartz cylinder (see Fig. 12) and provide a means for flowing nitrogen at high pressure from behind the cylinder down along the side and through radial holes to the under surface. Fig. 12 shows that the lower face of the quartz cylinder stands off about $\frac{1}{2}$ in. from the combustion chamber. The flow of nitrogen gas over and around the quartz and exhausting into

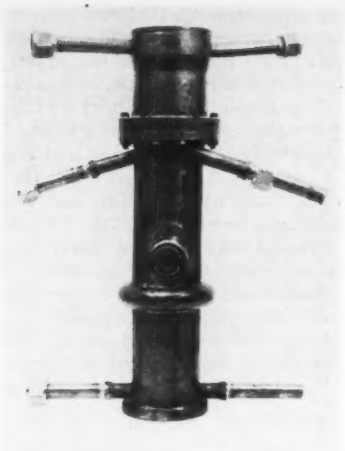

Fig. 10 General Electric 3-in. alcohol-oxygen water-cooled rocket with window bosses

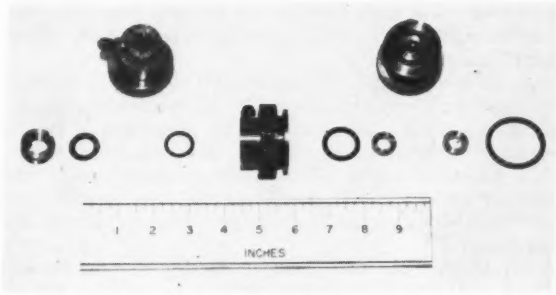

Fig. 11 In conjunction with assembly sketch Fig. 12 shows the structure of the windows. All seals made with O-rings. Designed for nitrogen flow at pressures of 500 psi

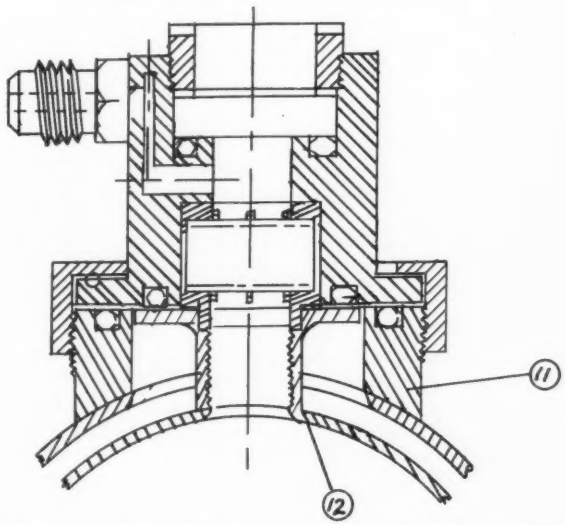

Fig. 12. Shows details of window construction. Design allows for thermal movement between inner and outer shells. Parts 11 and 12 are welded to rocket body

the combustion chamber cools the quartz and shields it from the combustion gases. The quartz surface on the flame side usually has a light deposit after a run.

The rocket wall where these windows were installed consists of two concentric shells between which cooling water flows in a helical path. It is important that there be no impedance to

the water flow and, secondly, that provision be made for a thermal expansion between inner and outer walls. Fig. 12 shows that effectively the width of the water jacket is increased at the window to compensate for loss in cross-section area of the helices due to the introduction of the inner tube. The water flows through two parallel helices between the shells. The inner tube is positioned so that it cuts half into one helix and half into the adjacent helix. It is important that there be no sharp corners. The weld was built up to form a slight fairing where the inner tube is joined to the inner shell, so as to avoid cavitation. A heavy threaded ring is welded to the outer shell (Fig. 12) concentric with the inner tube and surface ground flat with the inner tube. The window is fastened to the threaded ring and is in contact with the inner tube by means of O-ring no. 8. There is enough clearance between the lower washer and inner walls of the tube so that there may be relative motion between them.

Spectra

The experience gained in measuring exhaust temperatures showed the necessity of a careful study of the spectra. The temperature measuring apparatus, as normally used, isolates a region of continuous background approximately 150 Å wide. It is essential to know whether this region is free of line and band structure and whether the radiation is gray body following Planck's relation.

A new spectrograph was built for this combustion chamber work using a 60-deg extra dense flint prism and a Voigtlander F/7.2 22-in. lens, stopped down. The dispersion of this instrument is 45 Å/mm at 5000 Å. Eastman 4-in. × 5-in. infrared sensitive, type I-N emulsion plates were used. The apparatus was bolted in position in the firing chamber and used both with a normal 3-in. window rocket and with the G-E slit rocket.

Thirteen spectra were obtained, but not all of these were usable. The fifth plate was only a $1^1/_2$-sec exposure because the rocket was shut down. There is no sodium D line in this exposure and no structure of any sort in the spectrum. This plate and the following one were reticulated in the developing process. The sixth plate does show the presence of the D line.

Plates seven and eight are fairly good. Plate eleven is a very light spectrogram. The remaining two plates taken of the G-E slit rocket are very dense and show structure in the infrared.

Reduction of Rocket Spectra

Although, for our purposes, it is sufficient to determine a wave-length interval in which the rocket flame is a gray-body emitter, it is more informative to plot the flame continuum over the visible region against a background of theoretical black-body curves. This plot then shows how well the flame approximates a theoretical gray body, indicates the region and amount of deviation, and indicates the approximate temperature of the flame if its emissivity is known.

The reduction technique for the spectral plates is as follows: The spectrograph is set for minimum deviation in the yellow-green region. With a specific slit width it was found that a 3-sec exposure gave a spectrum of the rocket flame ranging in density within the region 0.5 to 2.5. It was decided that all spectra would be taken in 3-sec exposures, although it was not possible in practice to adhere strictly to this. The helium spectra was photographed adjacent to the flame spectrum. Twelve prominent helium lines in the visible region furnish the wave-length scale. In the laboratory the spectrum of the calibrated tungsten strip lamp was taken through a step density wedge. The exposure time was 3 sec and the spectrum plate was from the same box as those used to observe the rocket. The tungsten was of such a brightness that its spectrum gave approximately the same density range as the rocket. The plates of the rocket spectra and the calibration spectra are given the same processing. Also adjacent to the tungsten spectrum is a helium spectrum. The densities of the steps on the step wedge were read with a densitometer and transmissivities of the steps computed from the relation

$$\text{density} = -\log \text{transmission}$$

The radiation of energy from the strip lamp is computed as a function of wave length for the specific temperature used in making the calibration spectrum.

The product of the radiancy of the strip lamp at each wave length and the transmissivity of the step wedge is a number proportional to the energy that falls upon the slit of the spectrograph. The geometry of the system is such that the spectrum of the strip lamp appears to be composed of seven steps. Thus, at each wave length, seven density readings are obtained corresponding to the seven steps of the density wedge. The densities as read are functions of emulsion sensitivity, contrast range, dispersion of the prism, selective absorption in the instrument elements, slit width, and many other less important factors. These factors are identical in effect for rocket exposures and the comparison calibrated exposures. Thus it is possible to read the densities at each wave length and plot these densities versus the computed incident energies; actually, of course, numbers in proportion to the energies. The plate is reduced by reading its densities versus wave length with a densitometer. Then from the calibration curves that look like Fig. 13, one reads off the "energies" corresponding to the densities. These energies are in arbitrary units, i.e., they are really numbers in proportion to the energies.

As a check of the system, we have reduced the tungsten plate with a lamp set at 2475 K. This is shown in Fig. 14.

Using this technique we have made a careful study of rocket run no. 2402. This is plotted in Fig. 15. This spectrum (Fig. 15a) was measured by Mrs. E. L. Miller, by J. B. Gilstein, and by J. H. Hett. The points shown are the weighted

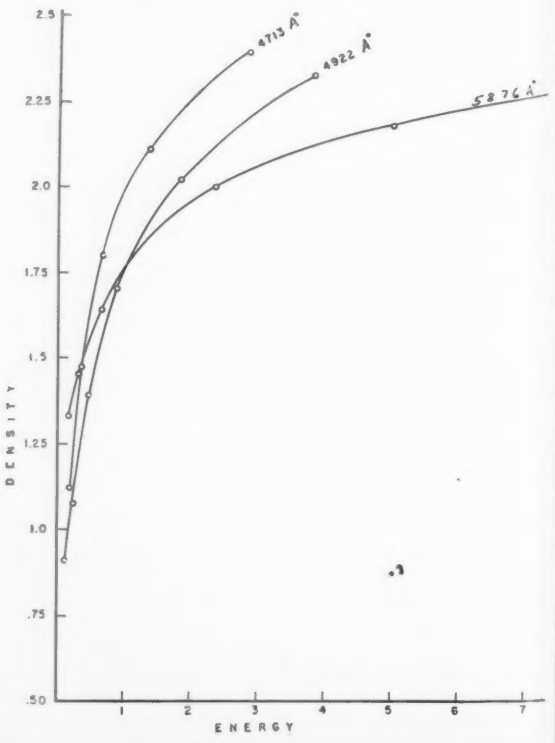

Fig. 13. Plot of density versus incident energy through the spectrograph for type I-N emulsion as a function of wave length. The energies are computed from a knowledge of the temperature of the calibration strip lamp, its spectral emissivity at each wave length, the transmission of each step of the Eastman no. 2 step wedge and the dispersion of the spectrograph prism as a function wave length. The energy scale is shown in arbitrary units.

Table 2 Rocket spectra Eastman type I-N plates

	General Electric run no.	Exposure, sec	Evaluation	
1	2389M1	20	Badly fogged; secondary images due to internal reflections in spectrograph	NaD lines resolved
2	2390M1	30	Badly fogged; secondary images due to internal reflections in spectrograph	NaD lines resolved
3	2391M1	30	Badly fogged; overexposed	.....
4	2392M1	5	Spoiled in development process	.....
5	2393M1	2	Spoiled; reticulated	NaD lines absent
6	2394M1	5	Spoiled; reticulated	NaD lines plus others
7	2402M1	5	Good	NaD lines present
8	2403M1	5	Good	NaD lines present
9	2405M1	5	Dense	Shows line and band structure
10	2406M1	6	Light	Shows line and band structure
11	2407M1	3	Very light	Shows line and band structure
12	Nozzle end of slit rocket	3	Extremely dense	Shows line and band structure
13	Head end of slit rocket	3	Extremely dense	Shows line and band structure

ones for all three observers. The spectrum which is typical shows an anomalous peak at approximately 4700 Å. Also, the slope from 5000 to 6200 Å differs considerably from that of a true Planckian curve. The spectral regions actually used for the temperature apparatus are 150 Å wide centered at 4930 and at 5310 Å.

In view of the departure of the observed spectra from gray-body radiation, one cannot speak strictly of temperatures. Thus in this paper we refer merely to "indicated temperatures." The spectra also show the necessity for further spectral work on rocket combustion chambers at different points along the rocket axis.

Indicated Temperature Measurements

The initial runs with the temperature instrument (5) showed that modification of the circuits would be necessary to reduce the gain. Because the deposits on the windows were different one run from the next, it was necessary to adjust the gain during the run.

From July 9 to July 19, 1951, temperature records were taken of combustion chamber flames.

From August 7 to August 9, 1951, attempts were made to use the Kurlbaum method of checking the average temperature and emissivity of the combustion chamber flame. The indicated temperature was approximately 2700 K, but the proba-

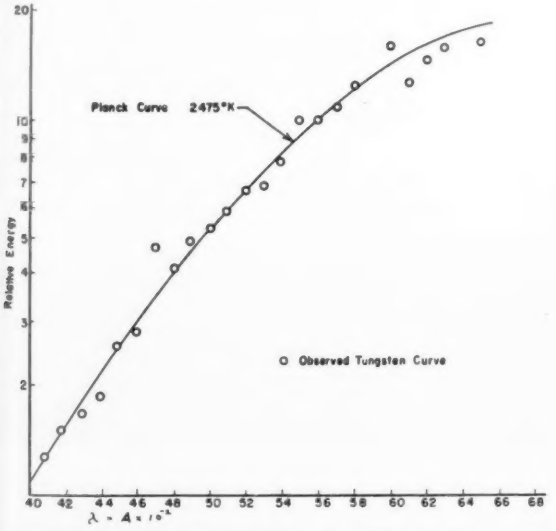

Fig. 14 Observed spectral curve of tungsten strip lamp set at 2475 K as a check upon entire reduction process

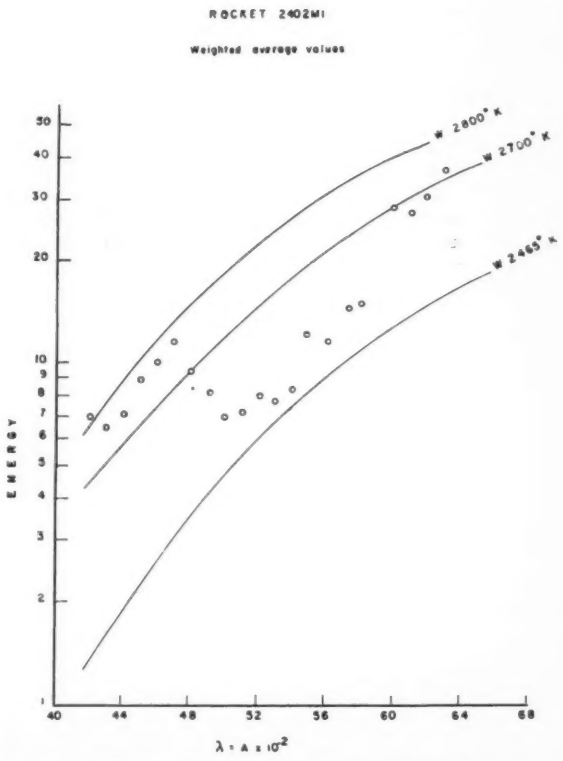

Fig. 15 Radiation from rocket no. 2402 plotted in a Planckian field. Position of the curve in ordinate is arbitrary

Fig. 15a Spectra of rocket run no. 2402. This run was reduced and is plotted in Fig. 15

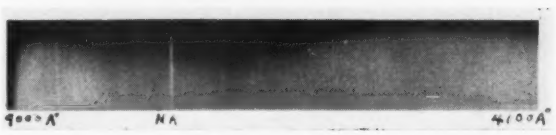

Fig. 15b Spectra of rocket run no. 2405. The original negative shows additional band structure not reproducible here

Table 3 Summary of indicated temperature observations

No. 2523 July 12, 1951		No. 2524 July 12, 1951		No. 2525 July 13, 1951		No. 2526 July 13, 1951		No. 2527 July 13, 1951	
Filter, 5310 Å		Filter, 5310 Å		Filter, 5310 Å		Filter, 4920°		Filter, 4920°	
Film speed, 30 in./sec.		Film speed, 40 in./sec.		Film speed, 53 in./sec.		Film speed, 40 in./sec.		Film speed, 40 in./sec	
Pressure on window		Pressure on window		Pressure on window		Pressure on window		Pressure on window	
Nitrogen, 500 psi		Nitrogen, 400 psi		Nitrogen, 400 psi		Nitrogen, 500 psi		Nitrogen, 500 psi	
Window transmission, 42%		Window transmission, 42%		Window transmission, 50%		Window transmission, 71%		Window transmission, 71%	
Emissivity, 0.47		Emissivity, 0.47		Emissivity, 0.47		Emissivity, 0.47		Mirror reflection coefficient, 83%	
	°K		°K		°K		°K	Average pts. Emissivity	°K
High pt.	2782	Low pt.	2775	Med. high pt.	2641	Low pt.	2714		2708 = 0.31
Low typical	2700	High pt.	2845	Average pt.	2601	Average pt.	2757		2707 = 0.50
Average pt.	2735	Average pt.	2827	Med. high pt.	2650	Average pt.	2776		2666 = 0.56
Screaming max.	2759	Average pt.	2832	Low pt.	2567	High pt.	2788		2673 = 0.40
Screaming max.	2753	Average pt.	2824			High pt.	2800		2700 = 0.58

ble error is undetermined. We believe this error to be high, due to the observational difficulties because of the high absorptivity of the flame. In view of this difficulty no attempt was made to determine emissivities by this method. The authors have observed optical absorptions of over 90 per cent in a quartz-walled rocket under certain conditions of running

Table 3 gives a summary of the temperature observations In only one of the five runs was it possible to obtain a satisfactory reading with the mirror channel. In this run no. 2527 the corresponding emissivities were determined. The average emissivity was found to be 0.47. On the other four runs the mirror channel gave approximately the same values as the black-body channel. All rocket runs were at approximately 300-psi chamber pressure with 3-in.-diam rockets using like-on-like injectors. Alcohol and oxygen were used throughout.

Also the Kurlbaum method, as previously noted, was found to be very insensitive; the differences between lamp plus flame and flame alone could be entirely accounted for by observational errors.

These difficulties with the Kurlbaum method and the mirror channel delayed publication of this paper for many months. The problem was resolved by studying the absorption in a G-E model rocket at the NYU Jet and Flame Laboratory. The combustion chamber of this rocket model is approximately 10 in. long by 1 in. high by $^1/_2$ in. thick, bound by two walls of quartz each 1 in. thick. By placing a calibrated strip lamp in back of this rocket, it was found that the optical absorption coefficient may be over 90 per cent in cases where some liquid spray may be in the field of view. Also some correlation was found between high absorption and rough burning.

It is thus our opinion that the observed radiation in some runs is largely from the outer regions of the combustion chamber and that the mirror channel of the flame pyrometer may thus be expected to duplicate the black-body channel. This apparently was the case for runs 2523, 2524, 2525, 2526. In computing the temperatures for these runs, an average emissivity of 0.47, as determined from no. 2527, was used. Fig. 16 shows a typical dual trace temperature as recorded on a dual beam tube. Timing marks are $^1/_{120}$ sec.

Method of Temperature Reduction

Immediately following the rocket recording, two calibrations of each of the two channels were made on the same film. First, each channel was calibrated using the strip lamp as the light source, with both combustion chamber windows in place. Second, the calibrations were repeated, this time with the rocket window on the side toward the strip lamp removed. Experience showed that the two rocket windows nearly always were dirtied to the same degree. Thus it was necessary merely to measure the transmission coefficient of a single window.

The technique of measuring the transmission coefficient (γ) was as follows. The two calibration curves of lamp temperature versus deflection on film for the single channel were used. Since equal deflection on the film means equal flux into the receiver, several pairs of corresponding lamp temperatures for equal deflection with and without the window were taken. Then the average of the values obtained by solution of the following equation was used.

$$\gamma = e^{c_2/\lambda}\left[\frac{1}{T_w} - \frac{1}{T}\right]$$

where

T_w = the apparent black-body temperature through the window
T = the apparent black-body temperature without window
c_2 = 1.433 cm °K
λ = wave length of filter used (0.531 for example)

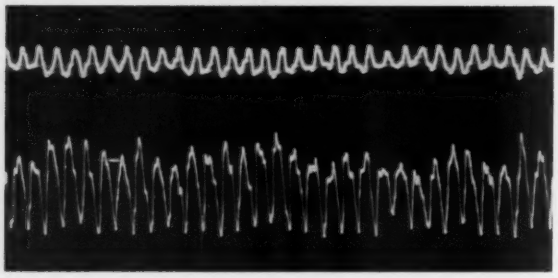

Fig. 16 Dual temperature trace of run no. 2523 which was unstable. Large amplitude trace is single channel; small trace is mirror channel

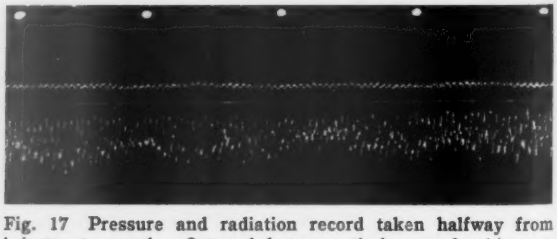

Fig. 17 Pressure and radiation record taken halfway from injector to nozzle. Interval between timing marks $^1/_{60}$ sec. Average pressure 300 ± 15 psi. Peak-to-peak amplitude 40 psi. Major frequency of oscillation 1320 cps. This portion of the record occurred about $1^1/_2$ sec after the start before the fuel pressure had reached a maximum

GAS DYNAMICS PAPERS INVITED——Abstracts are still being invited for the ARS-Northwestern University Gas Dynamics Symposium at Evanston, Ill., August 22–24. Papers on combustion instability, sprays, ignition, and laminar flame propagation should be sent, before April 15, to: *Gas Dynamics Symposium, Dept. Mechanical Engineering, Northwestern Technological Institute. Evanston, Ill., U.S.A.*

For the temperature determination the corresponding deflection points on each channel are measured to give for the mirror channel apparent temperature T'' and, for the single channel, apparent temperature T'. The intensity equation for two channels for this instrument has been given by Hett and Gilstein (5) as

$$I_B = \frac{I_L'^2 R\gamma}{I_L' R\gamma^2 + I_L' - I_L''}$$

R is the reflection coefficient of the mirror, determined in the laboratory, and γ the window transmission coefficient. I_L' refers to the single channel, the I_L'' to the mirror channel. This intensity equation is transformed to a temperature form using Wiens relation thus

$$c_1\lambda^{-5} e^{-c_2/\lambda T} = \frac{(c_1\lambda^{-5} e^{-c_2/\lambda T'})^2 R\gamma}{c_1\lambda^{-5} e^{-c_2/\lambda T''} R\gamma^2 + c_1\lambda^{-5} e^{-c_2/\lambda T'} - c_1\lambda^{-5} e^{-c_2/\lambda T''}}$$

Reducing to

$$\frac{-c_2}{\lambda T} = \ln R\gamma \frac{-2c_2}{\lambda T'} - \ln\left[e^{\frac{-c_2}{\lambda T'}}(R\gamma^2 + 1) - e^{\frac{-c_2}{\lambda T''}}\right]$$

which is solved for T.

Having determined the temperature, the emissivity e can be readily determined from the intensity relation $e = I_L'/\gamma I_B$.

Several simultaneous pressure and radiation records were also obtained using the NYU pressure gage. Both pressure gage and optical line of sight were at the same distance from the injector. Fig. 17 shows a typical pressure and radiation combination. Interval timing marks are $^1/_{60}$ sec. Average pressure 300 psi, peak-to-peak amplitude 40 psi. Major frequency of pressure and flame oscillation 1320 cps. We noted, and several observers have since confirmed, a close correspondence between flame and pressure maxima.

Acknowledgment

The authors wish to thank the staff of the Malta Test Station for the use of their facilities and for their co-operation at all times.

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2 "Studies Pertaining to the Measurement of Temperatures in a Detonating Explosive," OSRD Report 5618, Division 8, January 1946.

3 "Temperature Measurement on Complex Flames by Sodium Line Reversal and Sodium D Line Intensity Contour Studies," by H. M. Strong, F. P. Bundy, and D. A. Larson, Third Symposium on Combustion (Madison), 1949. Final Report R-50A0506, Project Hermes, U. S. Army Ordnance, General Electric Co.

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6 *Zeits. F. Tech. Physik*, A. Schack, vol. 6, May 1925, p. 530.

7 Progress Report for Period Aug. 1–Oct. 1, 1952, subcontract in connection with Contract No. DA-30-115 Ord-23 from Jet and Flame Laboratory, New York University to General Electric Co., Aeronautic and Ordnance Systems Division, Schenectady, N. Y.

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Jet Propulsion News

Alfred J. Zaehringer, American Rocket Company, Associate Editor

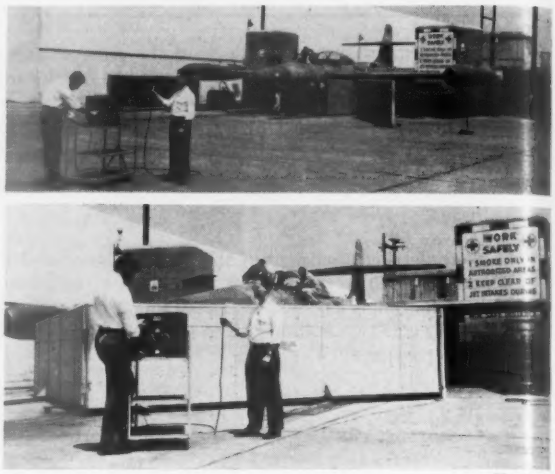
Jet Mufflers

IN TESTING and operating today's high-thrust jet engines in the test stand or in a preflight aircraft checkout, the problem of noise control is of considerable importance. The noise level of a jet engine may be about 130 decibels at a distance of 300 ft, in comparison to 100 decibels for a 2500-hp piston engine or the 55 decibels of an automobile engine. Two methods of decreasing the noise are: (1) increasing the distance between the engine and the ear, and (2) using deflectors or mufflers. Acoustical shielding such as a simple blast wall can reduce the noise level by 25 decibels but may cost as much as $60,000. Several methods of shielding are of interest.

North American has employed a sound abatement chamber at its flight line checkout of its F-100 Super Sabres. The tail pipe of the supersonic flighter juts through an opening in the silencer unit where it is fitted with a nearly soundproof asbestos collar. The silencer chamber has double steel walls and is filled with sand 3 ft thick. A water-cooled muffler is also used, which delivers water at a rate of 480 gpm sprayed into a 45-ft pipe.

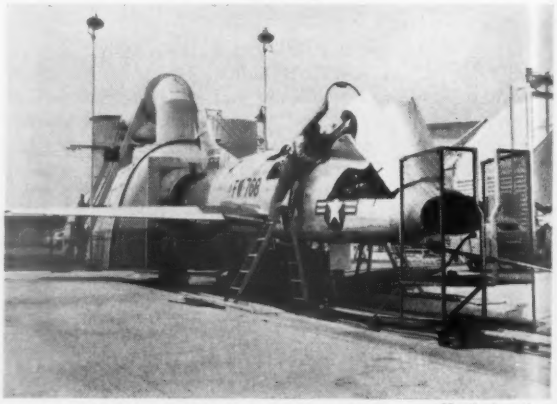
In ground run-ups of its F-89D Scorpion, Northrop has used the soundproof door technique. Costing over $50,000 each, the enclosures are placed around the aircraft. The doors are made of steel covered by sound-deadening padding and enable personnel to work at more comfortable sound levels.

Ryan has recently spent $50,000 just to muffle one of its new jet engine test cells. The Ryan cell is a monolithic concrete vault with openings for air inlet and jet exhaust. Since the massive 2-ft thick walls conduct very little sound, attention was directed at the openings. The Industrial Sound Control Corp., of Hartford, Conn., supplied units to trap and absorb the various types of sound emanations. Each unit is a perforated metal structure of sinusoidal configuration. These are filled with layers of glass fiber material held in place with steel wire mesh. The units are installed in overlapping labyrinths. In this installation, the sound intensity was reduced from 150 decibels to about 75 decibels in most frequency ranges. The acoustical intensity was thus reduced to about $^1/_{100}$ of its unmuffled value.



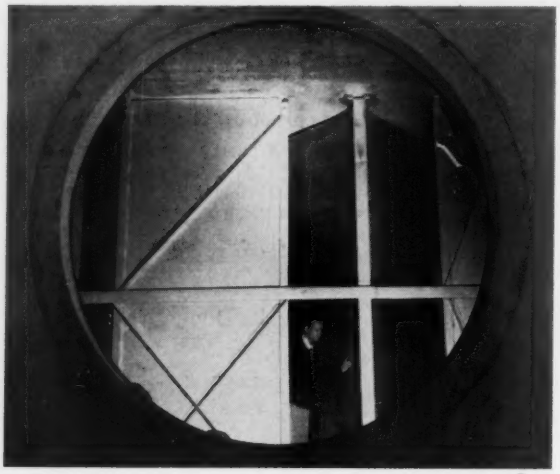
Northrop

Unmuffled sound at 100 ft (top) same as muffled sound at 15 ft (bottom)



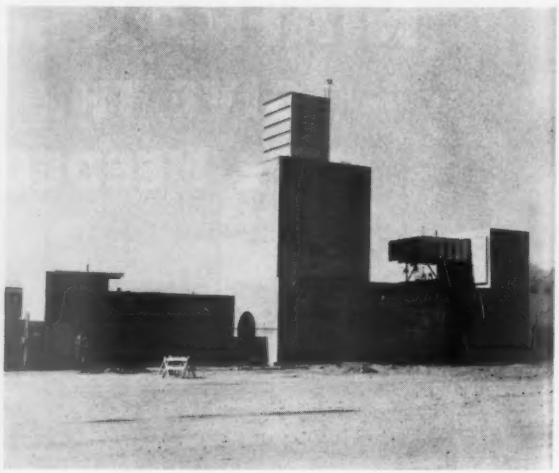
North American

F-100 silencing chamber



Ryan

Soundproof labyrinth for exhaust chamber



Ryan

Muffler-equipped test cell

EDITOR'S NOTE: The information reported in this Section has been selected from approved news releases originating with the Department of Defense, private manufacturers, universities, etc., and from published news accounts in journals and newspapers. The reports are considered generally reliable, although no attempt has been made to verify them in detail.

Rockets and Guided Missiles

THE Aerobee attained an altitude of 100 miles in a recent test at White Sands, and the data obtained will be used to construct the new Aerobee-Hi. The new rocket incorporates stainless steel construction and employs a chemical gas generator to pressurize propellants. Total weight will be about 1100 lb, less payload. Predicted altitude capabilities for the planned vehicle of 120, 150, and 180-lb. payload capacity are 202, 184, and 168 miles, respectively. Testing is scheduled for May.

Lt. Col. John P. Stapp attained a speed of 632 mph on a rocket powered sled at Holloman AFB, New Mexico. The sled, driven by 9 RATO bottles of 4500-lb thrust each, was accelerated to top speed in 5 sec and 2800 ft of distance. After burnout, the sled coasted less than $^1/_2$ sec and then braking—equal to 35 G—was accomplished in little over 1 sec. The only effects suffered by the officer were blood blisters from flying dust particles and two black eyes encountered during the sudden deceleration.

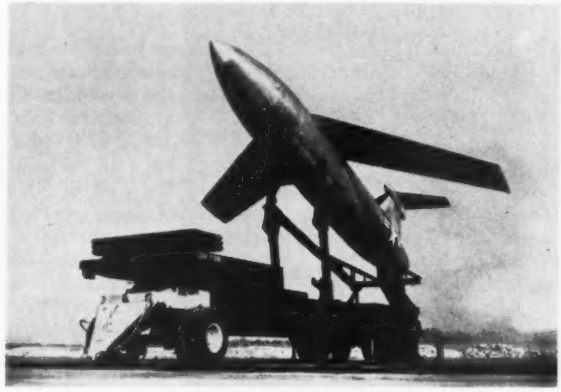
Nike is in for additional improvements in a program launched by Bell and Aerojet. A more powerful rocket motor to improve range and frangible booster casings are said to be in development. Meanwhile, in an answer to claims that Nike can knock down only outmoded aircraft, an official Army spokesman has stated that the present Nike can hit jet aircraft.

Sidewinder missile, developed by Philco for the Navy, is a new air-to-air rocket which is pod-mounted in jet aircraft wingtips.

Honest John rocket is going to replace some conventional cannon field artillery batteries, according to the Army.

A new liquid propellant rocket, AR III, was recently shown in the Salone delle Tecnica, Torino, Italy. Further details of the supersonic rocket, said to operate on a new principle, were not given. Designer is Dr. A. C. Robotti, ARS member.

Details have been released on the Matador zero length launcher. Essentially a 39-ft tandem axle semitrailer of 35,000 lb empty weight (photo), the launcher is used in con-



junction with a 38-ft, 15,000-lb transport semitrailer and contains a motor generator, blower, hydraulic pump, and wing rack. The mobile equipment also includes a 5-ton tractor truck and a 20-ton truck crane. The missile is mounted on a 3-point suspension system. Two balls and socket support the front end of the missile and point the B-61 at a 15-deg angle. Rear support is a bolt which is sheared at take-off. A typical launching begins by bringing the Matador jet engine up to full thrust and then igniting the RATO bottle, thus shearing the rear retaining bolt. At this point, the front supports swing forward and drop away from the missile which allows clearance for the booster motor. Launching can be

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made from any hard-packed earth surface, although concrete, macadam, or planking are normally prepared as a pad. Recent tests have shown the feasibility of launching jet aircraft by using this technique.

Soviet Missile Progress

COLLATION of scattered news items seems to indicate that the USSR is rapidly building up its missile hardware program. Most vigorous programs appear to be devoted to air defense. Missile launching sites at Severnaya Zemlya, Kola, Taimyr, Chukot, and along the Sea of Okhotsk were begun in 1948 and may be operated in conjunction with the large radar centers at Severnaya Zemlya and the New Siberian Islands. Two ground-to-air missiles have been reported. One is a modified Wasserfall for medium range interception. Probably available in larger numbers is the M-1 guided missile that resembles our Nike and Terrier. Vertically launched by a solid propellant booster, the M-1 has a liquid propellant sustainer system that gives it a maximum speed of about Mach 1.3 and an altitude of about 30–40 thousand ft (range unknown). Total weight is about 1500 lb (3300 lb with booster); sustaining thrust is 3000 lb for 30 sec; length is 15 ft; diameter is 15–20 in.

Jet interceptors may be armed with a unique air-to-air rocket now in the research stage. Called the M-100, this single stage rocket has a diameter of about 10 in. and is about 13 ft long. It weighs 990 lb and can carry a large warhead to a speed of Mach 0.9–1.3. The power plant employs a low-cost, composite-type, solid propellant (said to be petroleum-based) with a propellant specific impulse of about 150 sec. The standard Russian RATO, also using a solid propellant, appears to deliver 2900-lb thrust for 8–15 sec. However, the standard air-to-air missile is probably the RS-82 (3.24 in caliber) or the RS-132 (5.2 in caliber), both using double-base solid propellants.

Very little data are available concerning Soviet rocket artillery. Standard models are probably based on the old Katysusha or the improved RS-132. A new artillery development is the report of a long-range (over 50 miles) ground-to-ground, single-stage, ballistic missile employing a solid propellant power plant which develops about 500,000 lb sec impulse. Meanwhile, there are persistant reports of an improved V-2, available in operational numbers, with a range of about 300 miles. There also seems to be good evidence that a refinement of the V-1, powered by either a pulsejet or turbojet, exists. Range capabilities of up to 1500 miles and speeds of Mach 1 have been mentioned, and launching techniques developed at the Taimyr facility indicate a high possible launching rate from either ground pads or submarines.

There have also been numerous reports of manned VTO rocket interceptors. One is the modified German DFS-346, which lands tail first by means of auxiliary rockets and a drogue chute. Another, said to be in operation around key Soviet cities, is the Yak 21, which can exceed the speed of sound and is able to climb at a rate of about 12,000 fpm.

Meanwhile, Pravda reports that the USSR Academy of Sciences has established a Tsiolkowsky Gold Medal to be awarded for outstanding work in astronautics. Even the Russian attitude toward participation in the International Astronautical Federation seems to be more friendly. In addition, Moscow radio recently interviewed Prof. Dobronravov, who stated that the establishment of a Russian satellite would be possible "within a few years" and that space travel can be expected "in the very near future."

Thus there is every reason to conclude that the Soviets are engaged in a high level of rocket activity.

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ARS News

Seventeen Companies Active in Rockets, Missiles Become Corporate Members

LATEST group of companies to enroll as Corporate Members of ARS includes rocket, missile, and aircraft manufacturers; makers of missile guidance and control equipment; liquid and solid propellant producers; instrument manufacturers, and producers of gas turbine engines. They are:

Boeing Airplane Co., Seattle, Wash.—developer of three successful multijet airplanes, two pilotless aircraft, and a practical small gas turbine during the past ten years. GAPA, now obsolete, and the F-99 Bomarc, a ramjet-powered interceptor which is still highly classified, are the two missiles. The six-jet B-47 and eight-jet B-52 bombers and the tanker-transport 707 are the aircraft. The 175-hp Model 502 gas turbine engine is used as power plant in light airplanes, helicopters, trucks, and boats.

Carbide and Carbon Chemicals Co., New York—supplier of basic organic raw materials including fuels and propellants such as ethylene oxide, ethyl alcohol, and also additives.

Carborundum Co., Refractories Div., Perth Amboy, N. J.—manufacturer of refractory combustion chamber liners, nozzles and exit cones for rocket motors.

Allen B. Dumont Laboratories, Inc., Clifton, N. J.—research and production of electronic and electromechanical instrumentation, radar, missile guidance equipment, cathode-ray tubes, television receiving, transmitting and broadcasting equipment.

Firestone Tire & Rubber Co., Los Angeles—producer of the Corporal surface-to-surface missile for Army Ordnance.

General Dynamics Corp., New York—parent company of *Canadair Ltd.*, Montreal, and *Convair*, San Diego. The latter division is responsible for the Terrier surface-to-air missile and other classified missiles, as well as the Sea Dart, Hustler, and Pogo aircraft. Convair is also doing development work on nuclear-powered aircraft.

Grand Central Rocket Co., Redlands, Calif.—formerly the rocket division of Grand Central Aircraft, this organization is headed by C. E. Bartley, 1953 winner of the ARS C. N. Hickman Award for solid propellant contributions. Makes solid propellant rockets, boosters, gas generators, including rocket for the Loki missile.

Greenleaf Mfg. Co., St. Louis, Mo.—maker of rate and integrating gyros, servos, synchros, electronic equipment for missiles and aircraft.

Hercules Powder Co., Wilmington, Del.—solid propellant manufacturer, parent company of Allegany Ballistics Laboratory where solid propellants for many missiles, including the Terrier, have been developed.

M. W. Kellogg Co., Jersey City, N. J.—does research, development, design, and production of rocket cases.

W. L. Maxson Corp., New York—does research, development, and manufacture of electronic, pneumatic, hydraulic, and electromechanical systems and equipment for aircraft and missiles.

McDonnell Aircraft Corp., St. Louis, Mo.—maker of missiles, aircraft, ramjets, helicopters. Makes ramjet engine for the Talos.

Orenda Engines, Ltd., Toronto—formerly the engine division of *A. V. Roe, Canada, Ltd.*, manufacturer of gas turbine engines.

Philco Corp., Philadelphia—maker of guidance and control systems and developer of several classified guided missiles including the Navy's air-to-air Sidewinder.

Ryan Aeronautical Co., San Diego—producer of missiles, aircraft, and avionics. Developer of the Firebee jet-powered drone missile, the rocket motor for the Corporal, the Firebird air-to-air research missile, and producer of many jet engine and airframe components.

Thieblot Aircraft, Bethesda, Md.—research and development on aircraft and guided missiles.

Westinghouse Electric Corp., Pittsburgh, Pa.—research, development, manufacture of jet engines, airborne electronics, missile guidance systems, wind tunnel drives, aircraft electrical systems through Air Arm, Small Motor, Aircraft Gas Turbine Divisions.

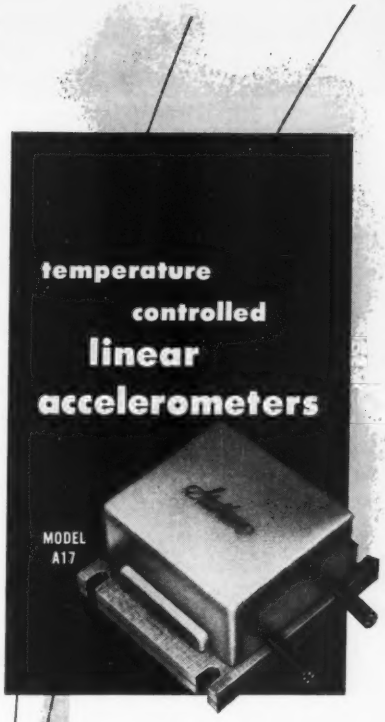
Tentative Program for Baltimore Meeting

THREE technical sessions, a luncheon, an oyster roast, and a boat trip to the U.S.N. Experiment Station at Annapolis

ARS Meetings Calendar

Apr. 18–22	ARS-ASME Spring Meeting, Baltimore	(see above)
June 19–23	ARS-ASME Semi-Annual Meeting, Boston	General
Aug. 1–6	Sixth IAF Congress, Copenhagen	(See p. 132)
Aug. 22–24	ARS-Northwestern University Gas Dynamics Symposium, Evanston, Ill.	Combustion
Sept. 19–21	ARS Fall Meeting, Los Angeles	General
Nov. 13–18	ARS-ASME Annual Convention, Chicago	General

Papers for all of the above meetings, except the Spring Meeting, are invited. Abstracts, or manuscripts should be submitted to the Program Chairman, American Rocket Society, 500 Fifth Ave., New York 36, N. Y. It is requested that abstracts be sent 120 days prior to the meeting date.



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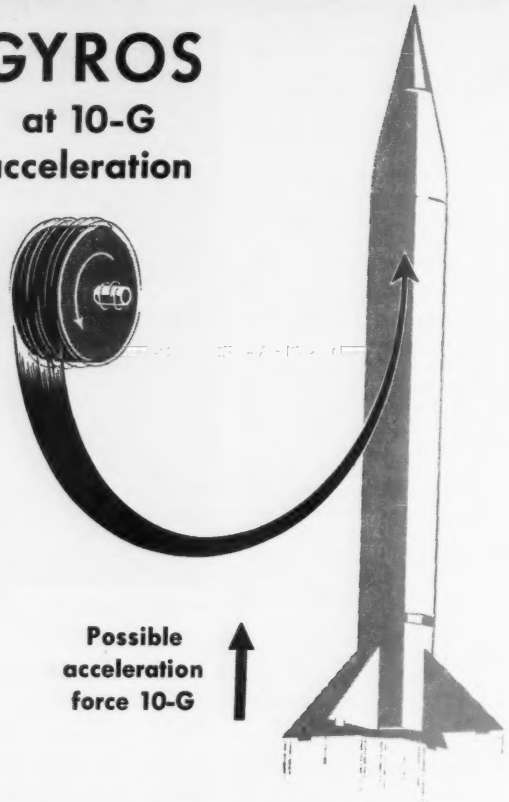

The gyroscope in a missile guidance system must be able to withstand acceleration forces up to 10 G's in any direction. This gyroscope, designed and developed by the Guided Missile Development Division of the U. S. Army and the Ford Instrument Company, will function under this acceleration. Tests have shown these gyros to be accurate to 1/50° per hour drift, or better.

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are tentatively slated for the ARS meeting (April 20–22) in conjunction with ASME's Spring Meeting in Baltimore, April 18–22.

Speaker at the luncheon on April 20 will be Dr. G. Edward Pendray, founder and Past President of the Society. Dr. Pendray will review the 25 years of ARS development and will show films of early rocket firings in the New York area.

Technical Events Chairman N. Elliott Felt, Jr., of the host Maryland Section, reports the following tentative schedule.

Session I—*Rocket Test Vehicles*

Chairman: E. T. Munnell, Glenn L. Martin Co.

Vice-Chairman: W. G. Purdy, Glenn L. Martin Co.

The Use of Rocket Vehicles for Upper Atmosphere Research—J. W. Townsend, Jr., Naval Research Laboratory

Flight Measurements of Aerodynamic Heating and Boundary Layer Transition on the Viking 10 Nose Cone—R. B. Snodgrass, NRL.

A Sunfollower for High Altitude Rockets—G. Granross, Aircraft Armaments, Inc.

The Worthwhileness and Applications of a Minimum Orbital Unmanned Satellite of the Earth (MOUSE)—S. Fred Singer, University of Maryland.

Session II—*Instrumentation in the Rocket Field*

Chairman: Major R. T. Franzel, Hqrs. ARDC

Vice-Chairman: Capt. George Johnson, Hqrs. ARDC

Photography from the Viking 11 Rocket—L. Winkler, Naval Research Laboratory

Instrumentation Techniques and Requirements for Rocket and Guided Missile Testing—H. B. Riblet, Applied Physics Lab., Johns Hopkins Univ.

Practical Factors in Rocket Telemetering—D. G. Mazur, Naval Research Lab.

Jet Propulsion Pressure Measurements at Audio Frequencies—Howland B. Jones, consultant, Jet Propulsion Research Program, Dept. of Aeronautical Engineering, Princeton University

Session III—*Manned Rocket Vehicles*

Chairman: Wm. A. Webb, Aircraft Armaments, Inc.

Vice-Chairman: Samuel Fradin, Miller Metal Products

Rotor Rocket Development for Helicopters—W. R. Brown, Reaction Motors, Inc.

Some Practical Aspects of Rocket Powered Aircraft—W. F. Moore and R. C. Smith, Bell Aircraft

Future Applications for Manned Rocket Vehicles—C. L. Forrest and R. B. Crisman, Bell Aircraft

A Communication Approach to the Design of Aircraft Instrument Displays—L. J. Fogel, Stavid Engineering, Inc.

Copenhagen papers

ACCENT will be on the unmanned satellite vehicle at the Sixth International Astronautical Congress slated for Aug. 1 to 6 at Copenhagen, Denmark.

Hans Buch Andersen, President of the Danish Interplanetary Society, host organization, has expressed this feeling in his request for manuscripts.

Deadline for papers is May 1. ARS members wishing to submit papers should send them, with a 10-line abstract and a short biography, to Milton Rosen, Naval Research Laboratory, Washington, D. C.

Section Doings

ARS SECTION PRESIDENTS

Alabama: JOSEPH WIGGINS, *Thiokol Chem. Corp.;* **Arizona:** R. H. HANSEN, *Hughes Aircraft Co.;* **Central Texas:** B. S. ADELMAN, *Phillips Petroleum Co.;* **Chicago:** B. J. CUSHING, *Armour Research Founaation;* **Cleveland-Akron:** JOHN SLOOP, *NACA;* **Detroit:** LAURENCE M. BALL, *Chrysler Corp.;* **Florida:** K. K. McDaniel, *Boeing Airplane Co.;* **Greater St. Louis:** NORTON B. MOORE, *McDonnell Aircraft Corp.;* **Indiana:** A. R. GRAHAM, *Purdue Univ.;* **Maryland:** W. G. PURDY, *Glenn L. Martin Co.;* **National Capital:** E. C. PAGE, *Page Communications, Inc.;* **New Mexico-West Texas:** R. C. SHERBURNE, *New Mexico A & M;* **New York:** C. W. CHILLSON, *Curtiss-Wright Corp.;* **Niagara Frontier:** T. ZANNES, *Bell Aircraft Corp.;* **Northeastern New York:** KURT BERMAN, *General Electric Co.;* **Northern California:** W. J. BARR, *Detroit Controls Corp.;* **Pacific Northwest:** R. M. BRIDGFORTH, *Boeing Airplane Co.;* **Princeton Group:** IRVIN GLASSMAN, *Princeton Univ.;* **Southern California:** C. M. MCCLOSKEY, *ONR;* **Southern Ohio:** W. J. MIZEN, *Bendix Aviation Corp.;* **Twin Cities:** J. J. SCHONS, *Univ. of Minnesota.*

Underwater Jet Propulsion

Two experts on propulsion devices for underwater craft spoke on Jan. 13 to the **Southern California** Section.

C. A. Congwer and G. McRoberts, manager and chief engineer, respectively, of Aerojet-General Corporation's Underwater Engineering Division, discussed the application of aerodynamic principles to the design of below-surface craft. They also dealt with the influence of duct losses on jet propulsion devices.

Electric Space Ships?

Dr. Ernst Stuhlinger, Redstone Arsenal scientist, elaborated on his idea for using electrically accelerated ions as a propulsive means for space vehicles at the December meeting of the **Alabama** Section. Dr. Stuhlinger first presented his paper at last year's IAF Congress in Innsbruck (JET PROPULSION, Jan. 1955, p. 48).

Chicago Hears Wiant

Harry W. Wiant, project engineer at Cook Research Laboratories, Skokie, Ill., gave a talk on the Cherokee and Skokie supersonic component test missiles before a Jan. 26 meeting of the **Chicago** Section. Mr. Wiant delivered a paper on the subject at the recent Annual Meeting in New York (JET PROPULSION, Jan. 1955, p. 55).

Roy Marquardt Speaks

The **Cleveland-Akron** Section heard Roy Marquardt, president of Marquardt Aircraft Co., give details on a ramjet application for a subsonic target drone at a Jan. 13 meeting, reports George R. Kinney.

A large audience heard Mr. Marquardt discuss general aspects of the ramjet, including the development of nose inlets to give 95% efficiency of pressure recovery, the effect of altitude on combustion efficiency, and the effect of Mach number on operating altitude. He described a 30-in. ramjet used on the Lockheed F-80 interceptor and a 48-in. unit requiring only a one-week ground test.

Pogo at Purdue

Details on the Pogo vertical take-off airplane were disclosed to an audience of 83 at the **Indiana** Section's Jan. 11 meeting.

Speaker Dr. E. L. Katz, senior engineer in the Thermodynamics Division of Convair, spoke to the group and showed films of the company's Sea Dart, F-102, and R34 in addition to Pogo, according to James A. Bottorff.

At a Nov. 5 meeting, ARS Director George P. Sutton of North American spoke on high thrust rocket engines.

Operations Research

A talk on the development of research studies on operations analysis by the Air Force was given to the **Maryland** Section on Jan. 18.

The speaker was Leroy A. Brothers, director of the Air Force's Operations Research program.

Space Flight Assembly

First venture of the **Detroit** Section into its educational program took place on Jan. 20 at the local Bryant Junior High School. David N. Buell, Section secretary and engineer from Chrysler's Missile Branch, spoke on space flight to morning and afternoon assemblies of students and to an evening PTA audience. The lecture, designed to present a factual report of scientific research in rockets and missiles, was illustrated by Martin Aircraft's "Horizons Unlimited" film on the Viking.

The lectures evoked many questions from the audiences. C. A. Gibson, publicity chairman of the Section, reports that very favorable comment on ARS and Mr. Buell have been received from the Science Teachers Association in the Detroit area.

A further step toward making the Section better known in the area was achieved on Jan. 31 when directors Richard B. Morrison and Arthur B. Ash appeared on a local television program to discuss astronomy and possibility of life on other planets.

Pacific Northwest Elects

The permanent slate of officers and directors for the **Pacific Northwest** Section is as follows: Robert M. Bridgforth, Jr., president; William Ramroth, vice-president; James C. Drury, secretary; Joseph A. Brousseau, Jr., treasurer; and W. Emmett Coon, Nathan S. Ruder, Henry L. Turner, James H. Fisher, Robert Plath, George W. Hetterick, and Stanley W. Leszynski, directors. Mr. Ramroth is chairman of the membership committee, Mr. Turner of the program committee, and Harold Lustig, public relations.

Weather Expert

Dr. E. J. Workman, president of New Mexico Institute of Mining and Technology and a distinguished authority on weather, spoke to the **New Mexico-West Texas** Section on Jan. 27. He reviewed Langmuir's theories on long-range weather forecasting and discussed atmospheric circulation of heat and moisture.

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Book Reviews

C. F. Warner, Purdue University, *Associate Editor*

Rocket Exploration of the Upper Atmosphere, edited by R. L. F. Boyd and M. J. Seaton, Interscience Publishers, Inc., New York, 1954, 384 pp. $11.

Reviewed by S. F. SINGER
University of Maryland

This book, published as a supplement to the well-known *Journal of Atmospheric and Terrestrial Physics*, is the report of the first major international scientific conference concerned with rocket exploration of the earth's upper atmosphere. This conference was held in Oxford, England, in August 1953, and arranged by the Upper Atmosphere Rocket Research Panel of the United States and by the Gassiot Committee of the Royal Society of London.

Since 1946, upper atmosphere research in the United States, with captured V-2 rockets and later with Aerobees and Viking rockets, has produced a large number of interesting and important results about the earth's upper atmosphere and about extraterrestrial radiations reaching the atmosphere. At the same time theoretical developments in these very fields have been made all over the world, but especially by the group of atmospheric physicists of the Royal Society of London organized in the Gassiot Committee. The Oxford Conference resulted from the need for a direct exchange of information between rocket experimenters and theoretical physicists interested in the upper atmosphere. It was the first such opportunity for an international discussion of problems of the upper atmosphere in the light of modern rocket experiments. The present volume presents the forty-odd papers of the conference, corrected and updated by the authors and intergrated by the extremely able team of editors. As a collection of papers, the book does not approach the unity of a monograph on the subject; however, it represents our most up-to-date account of results of rocket experiments and theoretical interpretations. Many of the papers describe results which have not been published elsewhere; for example, the Signal Corps technique for exploding grenades to obtain upper atmosphere temperatures, or the University of Iowa technique for launching rockets from high altitude balloons.

The first section, entitled "Rocket Techniques," groups five papers describing properties of rocket vehicles important to upper atmosphere experiments. The second group of papers, under the heading of "Pressure, Temperatures, and Winds," presents not only results from rocket experiments but also describes complementary techniques such as radar and visual determinations of meteor trains, and measurements of traveling disturbances in the ionosphere. The third section deals with the composition of the high atmosphere and includes a number of papers on the techniques and results of atmospheric sampling in rockets, mass spectrometry from rockets and studies of the ozone distribution by optical and chemical means. The fourth section, which deals with the ionosphere, solar radiation, and geomagnetic variations, discusses ionosphere propagation measurements with rockets, direct exploration of ion densities by means of probes, rocket measurements of electric currents in the upper atmosphere, determinations of charge densities by means of radio-Doppler techniques, and finally a complete account of results on the solar ultraviolet and x-ray spectra which have for the first time been measured in rockets. There are also remarks by Professor Chapman on further ionospheric and auroral magnetic measurements which should be possible and important to do in rockets. The fifth section is a short one dealing with cosmic ray measurements by the Naval Research Laboratory Rocket Group. The sixth section groups together a series of papers mainly by British investigators on laboratory studies of fundamental processes in the upper atmosphere, such as the absorption of ultraviolet radiation and measurements of fundamental properties of collisions in gas discharges. The seventh and last section deals with theoretical considerations and interpretations of upper atmosphere rocket experiments and suggestions for new experiments with rockets.

The Pergamon Press should be congratulated on the extremely fine quality of pictures and on the great speed with which the volume appeared. It represents a timely review of the major results and interpretations of upper atmosphere rocket experiments.

Principles of Engineering Thermodynamics, by P. J. Kiefer, G. F. Kinney, and M. C. Stuart, John Wiley & Sons, Inc., New York, 1954, 529 pp. $7.75.

Reviewed by C. F. WARNER
Purdue University

Although this book is presented as the second edition of a book of the same title written by the two senior authors and published in 1930, it has been almost completely rewritten and much new material has been added. The more serious student of engineering thermodynamics or the teacher of thermodynamics will find this book a most welcome addition to his library. Some may find it somewhat tedious and verbose.

Part I is devoted to an extended discussion of energy, its forms, classifications, transformations, and equations. Care has been taken to distinguish between mass and weight. The application of the dynamic equation as well as the general energy equation to the analysis of steady flow phenomena is most welcome.

The distinguishing feature of this book is the superior presentation of the subject of availability of energy in part II and the second-law cycle analyses of part IV. The subjects of processes, reversible processes, cycles, reversible cycles, the Carnot cycle, and the Carnot principle are discussed in a logical sequence building up to the concepts of entropy and the availability of energy. The detailed exposition of these latter topics is augmented by numerous graphical illustrations. The numerical and graphical presentations of second-law cycle analyses of part IV give the reader a clear picture of the degradation of energy.

New material pertaining to the thermodynamic properties of fluids has been added in part III. Excerpts from Keenan and Kaye's "Gas Tables" are presented, and generalized compressibility charts, residual enthalpy charts, and residual entropy charts are given in the treatment of nonideal gases and vapors.

A brief discussion of atmospheric thermodynamics is given under the general topic of gas and gas vapor mixture.

While the treatment of thermodynamics of combustion is brief, the average engineer will find it adequate for most applications. The subject of chemical equilibrium is presented and some equilibrium constant curves given. Numerous examples illustrate the techniques and equations used in the solution of simplified engineering combustion problems.

Both the first and second-law analyses of the standard vapor and gas power cycles are presented in part IV. The majority of the material devoted to gas turbine cycles deals with stationary or shipboard applications; however, one example of a thermojet propulsion cycle analysis is given.

The last one hundred pages of the book are devoted to a treatment of compressible fluid flow. Flow equations in terms of total temperatures, total pressures, and Mach numbers are given. A chart for the graphical solution of ideal gas adiabatic flow problems is presented together with several numerical examples illustrating its use.

In conclusion this reviewer feels that the authors are to be commended for their presentation of this most difficult, broad, and somewhat controversial subject. One major omission should be pointed out, however: practically no references are given or additional literature cited.

Elementary Meteorology, by G. F. Taylor, Prentice-Hall, Inc., New York, 1954, 357 pp. $5.95.

Reviewed by W. W. BRIGGS
Purdue University

This book not only serves as a foundation for advanced study of meteorology but also furnishes the background of basic weather knowledge essential to students of geography, agriculture, biology, engineering, and other sciences and human activities in which weather is an important factor. A number of new ideas in the realm of meteorology have been touched upon briefly, but sufficiently to arouse the interest of the reader in some of the challenging new fields.

In the first chapter, although it is brief, the author presents a stimulating account of present-day ideas concerning the origin of the atomic species and the galaxies,

stars, and planets that populate the universe. A good description, including pictures, is given of the instruments and methods used in observing and measuring atmospheric conditions. This is followed by a discussion of the interrelation of the various weather elements. Wind and atmospheric circulation, including streamline analysis and jet streams, are well covered. A chapter on the physics of condensation and precipitation adds completeness to the book.

The chapter on air masses is excellent. The author discusses the various types of air, their source regions, their properties, and the types of weather which they produce. Characteristic curves, on both the Stüve and Rossby diagrams, are included for all the more important air mass types. A well-written description of frontogenesis and frontolysis is found in the chapter on fronts and storm structure. In that portion of the book devoted to violent local storms a brief account of the electrical phenomena of a thunderstorm is added. Factors affecting tropical weather are treated separately.

A series of analyzed weather maps is included in the chapter on weather charts and diagrams. Many techniques of present-day forecasting are explained in a fascinating manner. The author gives a simple explanation of the principles of climatology and a concise summary of the main features of the major climatic regions of the world.

The discussions are necessarily brief and incomplete; therefore, much interesting and valuable material has been omitted. To supplement this, an adequate list of reference books is to be found at the end of each chapter. Mathematics has been used only when essential to the complete understanding of a concept. The book is well illustrated throughout, and many useful tables and charts are found in an appendix.

Statistics for Technologists, by C. G. Paradine and B. H. P. Rivett, D. Van Nostrand Co., New York, 1953, 288 pp. $6.75.

Reviewed by I. W. Burr
Purdue University

This book should prove a valuable addition to the growing literature of statistics for physical scientists. The thirteen chapter headings give the scope of the book: Introductory; frequency distributions, statistical parameters; probability binominal distribution; Poisson's distribution, normal distribution; sum of squares of normal variates, goodness of fit; small samples, "Student's t," variance ratio; quality control; sampling inspection schemes, theory of errors; method of least squares; correlation; analysis of variance; principle of maximum likelihood, probit analysis. A good many derivations and proofs are included and much of the language is in mathematical form. However, one who has command of the calculus should have no real difficulty in reading it completely. Illustrative examples are good and there are sufficient problems for a complete course. Answers are included, which is extremely helpful for the self-taught student. The only criticism this reviewer had was the seem-

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ingly too brief treatment of a number of topics. This might make it difficult as a text for some students or readers, but does not handicap it as an excellent reference book.

The New Warfare, by Brigadier C. N. Barclay, Philosophical Library, Inc., New York, N. Y., 1954, 65 pp. $2.75.

Reviewed by J. L. Brown
Ramo-Wooldridge Corporation

In this book the author, known to some as editor of *The Army Quarterly,* has given a compact account of the evolution of modern warfare and his views of the present "cold" war which he discusses under the term "the new warfare." The reviewer strongly recommends the reading of this small book to all who are interested in a very reasonable interpretation of how the world has reached its present state, what is likely to happen next, and what we should do in carrying on "the new warfare."

Whether it is possible to extrapolate from the history of earlier wars and thereby predict the size and frequency of future wars may be open to doubt in view of the changing probability situation. However, Barclay's development of the hypothesis that we are now in a new type of war and must fight every phase of it with intelligence and vigor is very logical.

Forschung zwischen Luftfahrt und Raumfahrt, by Eugene Sänger, Verlag Walter Pustet, Tittmoning OBB, 1954, 93 pp. $0.98.

Reviewed by Paul P. Datner
Aerojet-General Corporation

This little book is a concise discussion of research at the boundary between aeronautics and astronautics. Topics such as the scope of the work required to advance aeronautics and to make the exploration of space possible, approaches to the problems, applicability of various means of propulsion, the technical problems to be encountered, etc., are listed and classified. Piston-engine propeller propulsion, turboprops, turbojets, ramjets, solid- and liquid-propellant rockets, thermo-nuclear propulsion, and photon rockets are considered with respect to their potential applicability. Sänger concludes that only turboprops, ramjets, and photon rockets hold real importance for the future, and will be used in such vehicles as subsonic turboprop airplanes, turboprop helicopters, ramjet-propelled supersonic aircraft, helicopters with ramjets on the rotor blades, supersonic aircraft, and space ships propelled by photon rockets. Sänger believes that rockets using solid and liquid propellants will be used only as take-off boosters and as gas generators for wind tunnels, and that piston-engine propeller, turbojet, and thermo-nuclear propulsion, together with solid- and liquid-propellant rocket sustainers, are of only temporary significance.

Sänger has attempted to categorize the problems encountered in aeronautical and astronautical research and to evaluate their relative importance. The classification he has developed should prove stimulating to everyone interested in these topics.

Technical Literature Digest

M. H. Smith, *Associate Editor,* **and M. H. Fisher,** *Contributor*
The James Forrestal Research Center, Princeton University

Jet Propulsion Engines

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Rocket Propulsion Engines

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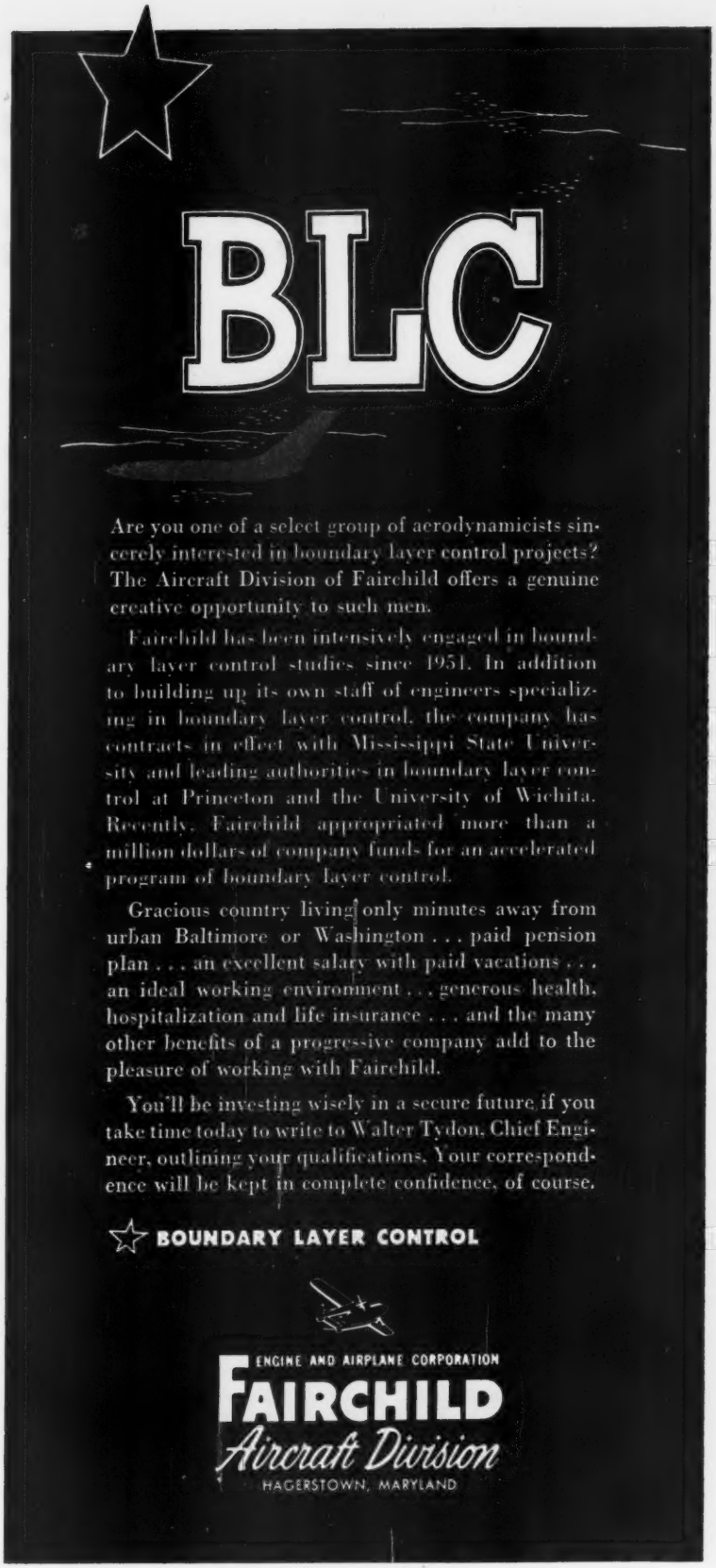
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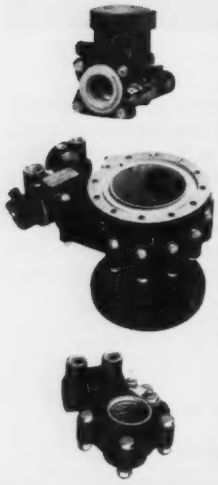

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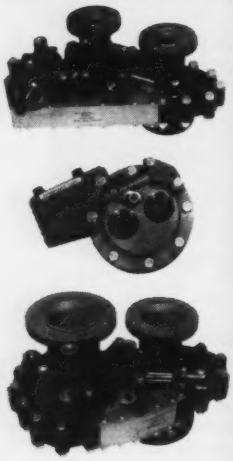

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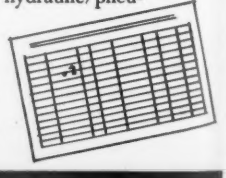

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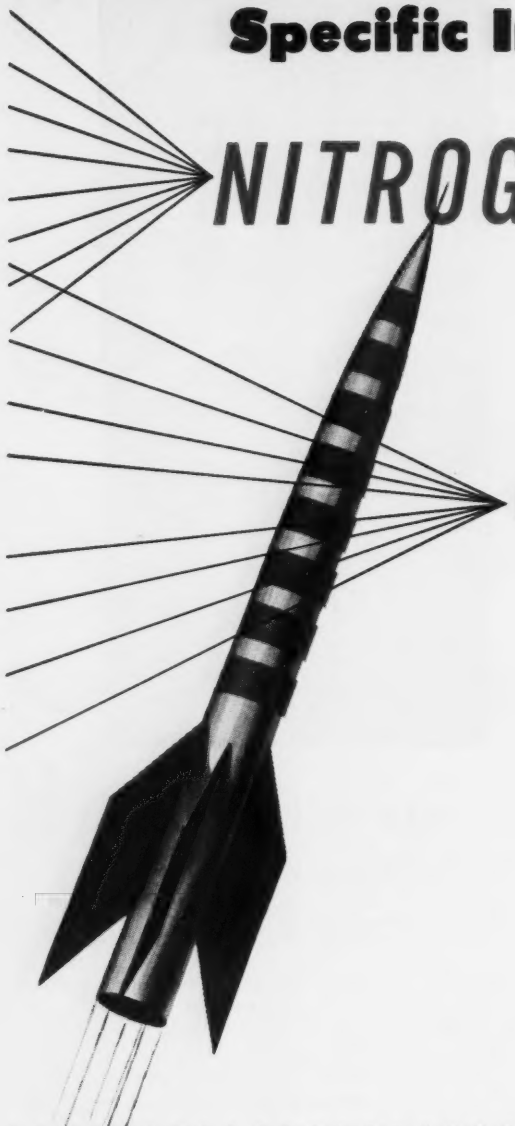

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1. **ENERGY**—performance exceeds that of hydrogen peroxide, red and white fuming nitric acid, mixed acids.
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Write today for full details. Available in 125-lb. steel cylinders, and 2000-lb. containers.

N_2O_4 compares favorably with the best propellants in every important category:

Molecular Weight	92.02
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Freezing Point	−11.3°C
Critical Temperature	158°C
Latent Heat of Vaporization	99 cal/gm @ 21°C
Critical Pressure	99 atm
Specific Heat of Liquid	0.36 cal/gm −10 to 200°
Density of Liquid	1.45 at 20°C
Density of Gas	3.3 gm/liter 21°C, 1 atm
Vapor Pressure	2 atm at 35°C
Availability	Good

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